Technology and Policy Options for Reducing Industrial Air Pollutants in the Mexico City Metropolitan Area

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To

The Memory of My Parents

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Technology and Policy Options[1] for Reducing Industrial Air Pollutants in the Mexico City Metropolitan Area

by

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Abstract

Technology plays an important role in dealing with air pollution and other environmental problems faced by developing and developed societies. This research examines if technological solutions alone, such as end-of-pipe and process control technologies, can achieve substantial and sustained emissions reduction from the industrial sector in the Mexico City Metropolitan Area (MCMA). Environmental standards for most of the criteria pollutants have frequently been violated in the MCMA. Severe air pollution in the MCMA, and the roles of point and area sources, particularly industrial sector, are the prime motivating factors for this research. Industrial sources of air pollution play a significant role in aggravating the air pollution problem in the MCMA.

This research focuses on a 25-year horizon for socio-economic growth of the MCMA, and its implications on industrial energy demand, and pollutant emissions. I develop a simulation model to estimate industrial energy demand and emissions from the MCMA industrial sector. The model incorporates industrial growth rate, changes in the structure of industry and energy intensity, pollution control technologies, fuel-switching, technological progress, etc.

I find that the level of industrial activity, driven by the macroeconomic environment, plays a significant role in shaping the long-term industrial air-pollution trajectory in the MCMA. I use two cost measures for evaluating cost-effectiveness of various strategies. First, the direct cost, which includes capital, operation & maintenance cost. Second, the policy cost includes direct cost and the cost of foregone production due to policy of deindustrialization. Performance of a strategy is highly dependent on which measure of cost is chosen for the decision-making process. The abatement strategies which look attractive when only capital cost of the control technologies and investment in renewal of the production stock is considered, are no longer preferred when the policy cost is used.

When only direct cost is considered, deindustrialization dominates the list of cost-effective options. However, when total policy cost of options is considered, reducing the structure adjusted energy intensity (SAEI) emerges as most dominant option. Further, I use a

sectoral abatement approach to look at the cost-effectiveness and estimate the potential cost savings from market-based regulatory instruments in achieving emission reductions. I find that the savings from using flexible, market-based mechanisms are large enough to warrant a serious consideration in environmental policymaking to achieve air-pollution abatement goals.

On basis of the scenario analysis, I conclude that technology options alone are not sufficient to meet the industrial air pollution abatement goals in the MCMA. However, an aggressive implementation of technology and policy options can result in achieving sustained and substantial emissions reduction. The structural shift from high energy intensity industries to low energy intensity industries, and deindustrialization, moving the industrial activity away from the MCMA, should form an integral part of the policy making process. The current institutional framework in the MCMA to manage the environment is not geared to integrate the technology and policy options. A paradigm shift -- from environmental policymaking for industrial sector to industrial-environmental policymaking -- is needed for attaining substantial and sustained emissions reduction, so that policy options such as deindustrialization and structural shift can be incorporated in the environmental policy making for the industrial sector.

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[1] The term options here means alternatives to choose from, and not "...a contract that permits the owner, depending on the type of option held, to purchase or sell an asset at a fixed price until a specific date".

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Abbreviations

AGREA	Analysis Group for Regional Electricity Alternatives
ALAPCO	Association of Local Air Pollution Control Officials
BOD	Biological Oxygen Demand
Btu	British Thermal Unit
CAM	*Comisión Ambiental Metropolitana*
CFE	*Comisión Federal de Electricidad*
CFF	Clean Fuel Fraction
CLIOS	Complex Large-Scale Integrated Systems
CMAP	*Clasificación Mexicana de Actividades Y Productos*
COA	*Cedula de Operación Anual*
CONAE	*Comisión Nacional para el Ahorro de Energía*
DCF	Discounted Cash Flow
DF	Federal District or *Distrito Federal*
DOE	Department of Energy
EIA	Energy Information Administration
EM	State of Mexico or *Estado de México*
EPA	Environmental Protection Agency (USA)
GRP	Gross Regional Product
IEA	International Energy Agency
INE	*Instituto Nacional de Ecología*
INEGI	*Instituto Nacional de Estadística Geografía e Informática*
IPAT	**I**mpact = **P**opulation***A**ffluence***T**echnology
IPCC	Intergovernmental Panel on Climate Change
IPPS	Industrial Pollution Projection System
LFEE	Laboratory for Energy and the Environment
LGEEPA	*Ley General de Equilibrio Ecológico y la Protección al Ambiente*
MAC	Marginal Abatement Cost
MARI	Mexico Air Quality Research Initiative

MBI	Market-Based Instruments
MCMA	Mexico City Metropolitan Area
NAAQS	National Ambient Air Quality Standards
NESCAUM	Northeast States for Coordinated Air Use Management
NOx	Nitrogen Oxides
NSPS	New Source Performance Standards
PACE	Pollution Abatement Cost and Expenditures
PM	Particulate Matter
ppm	Parts per Million
SAEI	Structure Adjusted Energy Intensity
SEMARNAT	*Secretaria de Media Ambienté Y Recursos Naturales*
SENER	*Secretaria de Energía*
SMA	*Secretaria de Media Ambienté*
SO_2	Sulfur Dioxide
STAPPA	State and Territorial Air Pollution Program Administrators
TOD	Transit Oriented Development
VBA	Visual Basic for Applications
WDI	World Development Indicators
ZMVM	*Zona Metropolitana del Valle de México*

Chapter 1

Introduction

Technological progress, on the one hand, is considered a boon for humankind; on the other hand, it is also understood to be responsible for the environmental challenges being faced by humanity today. Some analysts have argued that technology-created problems, such as environmental degradation, can only be solved by technology (Bereano 1976). Analysts like Anderson (2001) have supported this notion and argued that air and water pollution-control technologies have been able to provide cost-effective solutions to the environmental problems. Other analysts, such as Faber (1995) and Huesemann (2001), have questioned this premise citing inherent limitations of technology. It is evident that, technology, and technical progress have an important role to play in dealing with the environmental problems. I examine the role of technology in dealing with the air-pollution problem in Mexico City[1].

In particular, I examine the role of structural shift in the industrial sector (from high to low energy intensive industries, or vice versa), end-of-pipe emission control technologies, energy intensity, and market-based regulatory instruments, in achieving environmental goals with specific reference to the industrial sources of air pollution in the Mexico City Metropolitan Area[2] (MCMA). First, I model the impact of structural shift in the industrial sector, energy intensity and macroeconomic indicators, on the energy demand of the MCMA manufacturing[3] sector. Then, I develop a simulation model, based on the IPAT[4] (discussed in detail in Chapter 5)

[1] Technically, Mexico City is a sub-set of the Mexico City Metropolitan Area. However, in this thesis I use the two terms interchangeably.

[2] The Mexico City Metropolitan Area (MCMA) is defined in Chapter 3.

[3] The terms industrial sector and manufacturing sector have been used interchangeably throughout the text. A detailed description of the sub-sectors included in the industry sector is provided in Chapter 3.

[4] The term IPAT is an abbreviation for the components of the following identity, Impact = **P**opulation x **A**ffluence x **T**echnology, see Chapter 5 for details.

family of models, to incorporate the impacts of control technologies, fuel-switching, and structure-adjusted energy-intensity on emissions from the industrial sources in the MCMA. The model allows me to carry out scenario analysis, taking into account various paths of technological growth and different levels of policy-driven emissions controls. Further, I have applied a sectoral marginal abatement cost (MAC) approach, and used the equimarginal principle[5] (see Kolstad 2000; Hanley et al. 1997) to estimate savings from the use of market-based flexible regulatory emissions reduction mechanisms, such as cap-and-trade or emissions taxes. I also investigate feasibility of market-based instruments in achieving air-pollution abatement targets by the industrial sector in the MCMA, and identify hurdles in implementing the policies such as cap-and-trade in the MCMA.

When only the capital cost of deploying end-of-pipe emission controls and investment in renewal of the capital stock for reducing energy intensity is considered, policies influencing the industrial output, such as deindustrialization[6], appear to be attractive. However, when the total cost of the policy, which also includes the cost of foregone production resulting from deindustrialization, is considered, strategies to increase capital investment -- such as renewing the production stock to reduce energy intensity and increasing population of the end-of-pipe emission controls in the industrial sector -- turn out to be more cost-effective.

The cost of technological solutions is small compared to the total value of production on a value-added basis, but the absolute cost is too large to easily win political approval from the stakeholders and policymakers. Further, I demonstrate, using scenario-based multi-attribute tradeoff analysis, the inability of the technological solutions alone to achieve sustained and substantial air-pollution

[5] Equimarginal principle states that, at the efficient level of pollution abatement, marginal abatement cost for all polluters should be equal.

[6] The term deindustrialization, taken from Regional Economics literature, means reduction in the industrial activity in a region or country.

reductions in the long run. A structural shift in the MCMA industrial sector, and policies to influence the level of industrial activity hold the key to achieving pollution abatement goals in the MCMA.

1.1 Motivation

The MCMA is one of the worst polluted megacities in the world (WDI 2003; Molina and Molina 2002; Molina and Molina 2004). Transportation, industrial, household, as well as the formal and informal commercial sectors are the major contributors to air pollution in the MCMA (SMA 2004). The MCMA has historically been the hub of Mexican population and economic growth (Pick and Butler 1997). The industrial and population growth in the city has put enormous pressure on the natural resources -- land, air and water -- in the valley. The Future Stories (Dodder et al. 2003, see Chapter 4 for a detailed description of the Future Stories) reflecting three socio-economic patterns of growth in the MCMA show that a significant increase in the air pollution is likely under various growth scenarios. Therefore, to achieve the air-quality improvement goals for the MCMA, we need to explore and exploit the emissions-reduction potential of every sector, to arrive at a least-cost solution for society. In the past, optimization models have been considered to be an effective tool to arrive at such solutions (MARI 1994). However, these solutions tend to be too narrowly prescriptive, and often do not pass the test of technical, economic and political feasibility under uncertainty (Connors 2001). Therefore, I use a scenario analysis approach to analyze an array of technology and policy options to achieve air-pollution abatement objectives.

A structural shift[7] in manufacturing sector is defined as a change in the relative share of output of industrial sub-sectors over time (IEA 2004). It is reflective of the

[7] Structural shift could mean different things in different contexts. For example, a structural shift in the economy means change in the relative shares of agriculture, industry, and service sectors to the total output. In this research the term structural shift refers to relative changes in the shares of monetary value of output of different sub-sectors, such as chemical, metal products, etc. to the total industrial economic output in a given region.

dynamic nature of the value of goods produced by the sub-sectors. Since the sub-sectors have different energy intensities, a structural shift can have significant impacts on the demand for energy, and thus on the air pollution. In the recent past, the MCMA has witnessed a shift from less energy-intensive sectors to more energy-intensive sectors. This structural shift is of concern for policymakers, as it means accelerating energy demand, and therefore increased air-pollutant emissions in the MCMA. It is possible to devise market-based economic instruments or command-and-control policy options for the direct control of emissions to realize abatement targets of a region by influencing the direction of structural shift.

The success of market-based solutions to achieve environmental goals, notably the sulfur dioxide (SO_2) emissions reductions achieved by the SO_2 emissions-trading program in the United States (see Ellerman et al. 2003; Joskow et al. 1998) has led to the belief that market-based mechanisms can achieve air-quality improvement objectives in a much more efficient way than conventional command-and-control approaches. The implementation of market-based regulatory instruments requires a strong institutional capacity, adequate legal framework, as well as effective monitoring and enforcement (Huber et al. 1998). However, a market-based environment policy experiment in Chile to reduce particulate emissions demonstrates that even with limited institutional capacity, market-based instruments can be advantageous over traditional command-and-control approaches to reduce emissions (Montero et al. 2002). Developing and developed countries that still rely on the command-and-control approaches for regulation may benefit from the use of market-based instruments to achieve the goal of reducing air pollution in an economically efficient manner. The industrial sources of air pollution in the MCMA provide a potential opportunity to implement market-based instruments. However, prior to implementing such a system, policymakers need to have a reasonable quantitative estimate of the potential savings realized by the use of market-based instruments, such as emissions trading or pollution taxes. I apply the equimarginal principle, using a sectoral approach, and estimate cost-savings (see Chapter 8 for details) from the application of market-based instruments for reducing emissions from the MCMA industrial sector.

The debate about the roles of technology and technical progress in leading developing and developed societies to a sustainable pathway has been, at best, inconclusive. Developing societies face enormous challenges to reconcile the economic development goals with the environmental protection.

I develop a simulation model to incorporate the impact of structural shift in the industrial sector on energy demand in the region. The energy intensity, the structure of the manufacturing industry, and the level of activity form the three key components I use to estimate industrial energy demand in the MCMA. The energy demand and consumption by a sector is directly linked to air pollution. However, combustion modifications, end-of-pipe emission-control technologies, and technological progress can alter the emissions trajectory of a sector. I have developed a model to incorporate these variables and develop emission scenarios. I use a multi-attribute tradeoff analysis approach to look at the combined performance of the technology and policy options and incorporate the interactions between the macroeconomic indicators and penetration rates of technology, as well as technical progress, to study the relative costs and impacts of air-pollution abatement options over a 25-year horizon for the MCMA industrial sector.

1.2 Theoretical Basis of Research

My research draws heavily upon a vast body of literature from a wide variety of disciplines. The literature on sustainability and sustainable development provides a conceptual framework for my research. There are two schools of thought, one believes that development and growth of technology can lead to a sustainable development pathway; the other believes that technology alone can not help us in attaining the goal of sustainable development and the reduction of consumption is the key to achieving the goal of sustainability. The debate about the role and inherent limitations of technology and technical progress sheds light on the current understanding and consensus (or lack of it) surrounding the ability of technical solutions to lead to a sustainable development pathway for developing and developed societies. The idea that every irreversible process leading to economic development and growth is bound to increase entropy of the universe, and thus is inherently unsustainable, is borrowed from basic thermodynamics. The environmental economics literature provides a framework for estimating sectoral air-pollution-abatement costs. Integrated assessment and scenario analysis literature provides a basis for the use of methodologies for quantitative analysis. Global climate change literature, particularly, *Special Report on Scenario Analysis* by the Intergovernmental Panel on Climate Change, IPCC (2000) and literature from the field of industrial ecology (Chertow 2001) provide a theoretical basis for the use of the IPAT identity for developing my simulation model. Regional economics literature uses the shift-share analysis to analyze the role of various factors affecting job-growth in a region. It has also been extended to analyze the role of factors affecting energy demand. Energy intensity and energy demand literature, for example, the studies by the Energy Information Administration (EIA 1995) investigating the roles of various factors affecting energy demand by the US manufacturing sector, and a recent study by the International Energy Agency (IEA 2004) provides insights into the role of structural shift and its impact on energy demand. The literature from air-pollution engineering and control technologies forms the basis of selection of air-pollution-control technologies for the simulation model. A detailed literature review is presented later in this chapter, and elaborated in relevant chapters as well.

1.2.1 Technology, Economy and the Environment

Analysts in thermodynamics literature have long recognized the irreversibility of physical processes and quantitatively related it to the increase in *entropy*. They have predicted "thermal death" of the universe when temperature differentials will no longer be enough to enable us to convert energy into a usable form, such as electricity. This logical conclusion of the second law of thermodynamics has caught attention of many environmental theorists and economists. Some theorists have concluded that science and technology have a limited, if any, role to play in alleviating our environmental woes (Huesemann 2001). They argue that the current reductionist and mechanistic approach of science and technology is inherently unsuitable to provide enough information to enable us to model complex environmental systems accurately. Moreover, all the activities or industrial processes that we undertake are inherently irreversible. Nevertheless, in practice, we see that many interventions based on science and technology provide reprieve from the environmental impacts of industrial processes. A wide array of air-pollution-control technologies and waste-management practices are testimony to this fact (see Gurjar 2001; Wark et al. 1998). In response to the apparent success of science and technology in achieving pollution abatement by the use of technologies, such as scrubbers and electrostatic precipitators, theorists state that these efforts seem successful because attention is focused on very specific objectives, but that life-cycle impacts of implementing those technological solutions are ignored (Ahmed 1995). It is interesting to note that, on the one hand, these theorists see inherent conflict and limitation between environment and technology, on the other hand, they argue that "development of ever more precise technologies will reduce the many uncertainties associated with the estimation of the extent and magnitude of environmental pollution" (Huesemann 2001, pp. 284).

The argument is that the conventional scientific approach has been mechanistic and reductionist, and therefore, inherently unsuitable for solving complex large-scale problems, such as environmental degradation. However, scientists, engineers, and policymakers have recognized these limitations, resulting in an increasing popularity and use of integrated approaches (see an application of such an approach in Molina and Molina 2002), which encompass a much broader set of issues and takes into account interactions among sub-systems. The Complex, Large-Scale Integrated System (CLIOS) framework, as proposed by Dodder and Sussman (2003) (also see Dodder et al. 2004; Vijay 2002) is an example of such integrated approaches. The CLIOS framework is not only being used to model and understand the dynamics of various elements of transportation systems, but is also being used to understand the feedbacks and interactions between sub-systems of a complex large-scale system, such as the environment and institutions charged with managing the environment. Use of a systems approach to reduce air pollution in the Mexico City is one such example (see Dodder et al. 2004; Vijay 2002). The use of an integrated framework to analyze issues in local, regional, and global air pollution (Molina and Molina 2002) and the use of scenario analysis (Connors 2001) to deal with such issues is a testimonial to the fact that the scientific community recognizes the limitations of conventional approaches to deal with complex environmental issues and has aptly come up with updated methodologies, tools, and techniques.

Briefly, proponents believing that there are inherent limitations of science and technology in dealing with environmental problems suggest that the total environmental impact can only be contained by reducing the population, and by reducing per capita consumption of goods and services (Ehrlich and Ehrlich 1991). The question is -- in light of these predictions -- what could or what should a growing economy, such as that of Mexico City, do to achieve the dual goals of environmental protection and economic development? How far can technology help in achieving these conflicting goals?

Anderson (2001) and Ahmed (1995) present evidence from the engineering literature on air and water pollution control to demonstrate that large reductions in environmental pollution have been achieved in the past at a relatively small fraction of the total cost of production. Anderson has also developed a simulation model to study the effects of technical progress on pollution abatement in a macroeconomic framework applied to developing economies.

Recognizing the inherent limitations of technology-based solutions in dealing with long-term pollution problems, in general, and air pollution in particular, I explore the role of technology and technological progress in achieving air-pollution abatement from the industrial sector in the MCMA over a period spanning year 2000 through 2025.

1.2.2 Structural Shift, Energy Intensity and Energy Demand

More often than not, air pollutant emissions are proportional to the energy consumption. Different industrial sectors require different amounts of energy to produce a unit of output. The amount of energy required to produce a unit of output (in physical or monetary terms) is defined as energy intensity. Several factors result in different energy intensity of various manufacturing sub-sectors (EIA 1995). The sectoral energy demand (E) is defined (IEA 2004) as a product of sectoral activity (A), and the structure adjusted energy intensity[8] (SAEI), or

$$\mathbf{E = A*SAEI} \quad \mathbf{(1.1)}$$

The total energy demand by a sector depends on the output or activity of the sector, energy intensity of the sub-sectors, and structure of the sector. The structure of a sector, sometimes also known as industry-mix, is the share of each sub-sector to the total sectoral output. Decomposition of the total sectoral energy demand helps identify the factors affecting the changes in the energy demand by the sector. IEA (2004) has used the decomposition of energy demand to identify drivers of

[8] Structurally Adjusted Energy Intensity, SAEI = ΣS_j*Ij , where j represents all sub-sectors, S represents structure of the sector and I represents energy intensity of sub-sector j. For details, see Chapter 6.

greenhouse gas emissions from manufacturing sectors of its member countries. Kumar (2003) has explored the energy intensity of the Indian manufacturing sector using an econometric approach, and identified the size of the industry and plant-vintage to be two primary variables affecting energy intensity of a firm. The US department of energy (EIA 1995) has analyzed changes in the energy intensity in the US manufacturing sector. Aguayo and Gallagher (2005) investigate the implications of economic reforms and development on the energy demand by the manufacturing sector in Mexico. Bernard and Côté (2005) have conducted a principle-component analysis to identify factors affecting energy demand by the manufacturing sector. Sheinbaum and Rodriguez (1997) have investigated the trends in the energy use in the Mexican industry and their impact on carbon dioxide emissions. Analysis of the MCMA manufacturing sector data (see Chapter 6 for a detailed analysis) indicates that share of the energy-intensive chemical sub-sector in the total industrial output has been increasing at the expense of the share of the metal products sub-sector (INEGI 2004), affecting total demand for the energy by the manufacturing sector

1.2.3 Market-based Regulatory Instruments

Stavins (2000) defines market-based instruments as "regulations that encourage behaviour through market signals rather than explicit directives regarding pollution control levels or methods." Huber et al. (1998) uses a definition based on the notion that market-based instruments must attempt to align private costs with social costs to reduce negative impact of environmental externalities. Market-based instruments and economic instruments are often used interchangeably. Technology can provide a wide variety of solutions with varying costs and efficiency, but to use technical solutions to achieve abatement goals in the most efficient manner, market-based instruments look promising. Apart from cost-efficiency, market-based instruments offer flexibility and incentives for innovation and creativity. While the conventional command-and-control approaches rely on setting technology or performance standards to achieve the desired levels of pollution from various sources, market-based instruments equalize the marginal abatement cost (MAC) for all the sources. The flexibility that market-based instruments provide to a polluter in achieving a given emissions reduction target is their main strength (Huber et al. 1998).

Recognition of the fact that MAC for pollution reductions from different sources are not uniform is the basis of how the market-based instruments achieve pollution reductions in economically efficient manner (for example, see Gilpin 2000; Kolstad 2000; Stavins 2000). This heterogeneity in pollution-abatement costs results from several factors, including but not limited to, location, production technology, input quality and tax structure. However, analysts do not understand much about the structure of the heterogeneity, its' relationship to the cost savings for different regulatory instruments, or its policy implications. Empirical data available about the abatement costs of different pollution sources are also not rich enough to enable us to understand the role of various parameters and the structure of this heterogeneity.

Why does the MAC of firms differ? Intuitively, the answer to this question seems obvious. As different firms use different factor inputs --they differ in production technology, vintage, size, location, management, processes, control technologies, level of pollution, and many other pertinent factors -- they have different production functions, and therefore heterogeneous abatement costs.

The fact that MAC is heterogeneous is very well known and forms the basis of market-based instruments to reduce pollution at the lowest possible cost. Consider the following statement by Hanley et al. (1997), "...MACs vary across sources is a key insight into why the cost-minimizing means of securing target reduction in emissions will involve different amounts of emission reduction across sources." Newell and Stavins (2003) write, "a key factor in affecting relative aggregate costs under alternative policy instruments is the heterogeneity of pollution control costs across sources." This clearly illustrates the importance of heterogeneity of pollution abatement cost. There are two basic approaches to understanding the heterogeneity and its structure. The engineering approach is a bottom-up approach that focuses on estimation of the abatement cost for a particular pollutant or that of a set of pollutants for a given plant, from a technical perspective. The Northeast States for Coordinated Air Use Management (NESCAUM) has carried out several studies that provide engineering estimations of nitrogen oxides (NOx) control costs for various technologies and facilities. The so-called economic approach estimates pollution abatement costs by looking at the production function, inputs of production, cost and substitutability of inputs, of a firm or a sector. Hartman et al. (1997) estimate the abatement cost of pollutants using this economic approach.

There are several categories of market-based instruments, with a range of individual instruments, some of which provide more flexibility than the others. Credit subsidies, tax or tariff relief, deposit-refund schemes, waste fee, emission fee, tradable permits, etc., are some examples of market-based instruments (see Huber et al. 1998). Two popular categories of the market-based instruments are price, and quantity instruments.

The price and quantity instruments are effective in meeting the environmental goals when there is uncertainty about MAC, and the marginal damage function. The Weitzman proposition (Kolstad 2000) is a rule of thumb for determining suitability of an instrument in achieving abatement objectives. It suggests that when there is uncertainty over MAC, the quantity regulations are preferred if marginal damages are more steeply sloped than marginal savings from emissions. If the slope of marginal savings is steeper than marginal damage curve, then price instruments, such as emission fees are preferred. Setting emission taxes equal to the MAC is considered an effective solution if revenue generation is also a goal along with emissions reduction. Emissions tax is an example of price instruments.

Quantity instruments are used when the total permissible quantity of local pollutants is fixed on the basis of health impact studies or some other suitable criteria, and participants exchange or trade emissions within the established emissions "cap". This is also known as a cap-and-trade mechanism. Use of emission bubbles, or SO_2 trading regime in the US, is an example of quantity instruments. Finding an equitable initial allocation, designing markets to allow emissions trading, and enforcement of property rights, are the key components for their success. The mechanisms used for initial allocation of the permits can have significant distributional impacts. Montero et al. (2002) use Chilean example to argue that if allocation of permits is based on historical emissions, it can be used as a tool by the regulator to determine exact emissions from various sources.

1.2.4 Estimating Air-Pollution Abatement Costs

There are two approaches to estimate the cost of air-pollution abatement. The engineering-economics approach, a bottom-up method, is based on collecting actual capital and operating cost of a given facility. The econometric approach often lumps a group of industries together to arrive at cost coefficients for various pollutants, of different industries.

1.2.4.1 The Engineering-Economics Approach

Pollution abatement technologies and their cost-effectiveness have been of great interest to regulators and firms. The literature about abatement costs and factors affecting the cost-effectiveness has largely emerged from studies sponsored or conducted by regulatory agencies, such as the US Environmental Protection Agency (EPA), or state regulatory or environmental policy agencies, such as Northeast States for Coordinated Air Use Management (NESCAUM). For example, to support implementation of New Source Performance Standards (NSPS), EPA (1999) investigated many control options and estimates their cost-effectiveness. In engineering literature, the cost-effectiveness is typically defined as dollar per tonne of pollutant removed over the lifetime of the control equipment. The cost-effectiveness estimates thus calculated are essentially an accounting exercise, where they take capital cost, capital recovery, operation and maintenance, and other such factors into account to estimate the total cost of a technology. For example, NESCAUM (1998) reports on many NOx control technologies for industrial boilers. Cost effectiveness (dollar per tonne pollutant removed) is reported as a function of many variables. The important ones are baseline NOx emissions, capacity factor, boiler size, baseline cost of fuel, relative cost of fuel, and the cost of feedstock (such as urea or ammonia for selective catalytic reduction). Generally, the cost-effectiveness exhibits economies of scale, i.e., for a given boiler type, fuel, and emission control type, the larger the size of the boiler (represented in pounds of steam output per million British thermal unit of heat input), the greater is the cost-effectiveness, i.e., fewer dollars per tonne of pollution abatement are required. However, *ceteris paribus*[9], the choice of feedstock between urea and ammonia changes the cost-effectiveness. The initial or baseline emissions and final emission levels also affect the cost-effectiveness of control equipment. One important distinction we see between the engineering and economics literature is that the engineering literature, while aware of the differences between different sectors, does not pay much attention to the differences in the aggregate cost-effectiveness data arising because of differences in the sectors. Whereas the economic literature assumes that abatement cost is a function of sector type, and often ignores the intra-sector heterogeneity. NESCAUM (2000) studied NOx control technologies for small and medium industries, and reported the cost effectiveness based on size and type of the equipment, irrespective of the industrial sector in which it is used. The implicit assumption seems to be that any industry can choose any of the options available as long as it meets its technical requirements. There is very little, if any, restriction in the choice of technology resulting from the nature of the industry's production or inputs. This approach essentially assumes that

[9] *Ceteris Paribus* is a Latin phrase for "all else being equal". It is commonly used in economics literature to isolate descriptions of events from other potential environmental variables.

technology retrofit solutions are universal, and plant location and availability of fuels or other inputs for control technology have a very limited role to play.

The State and Territorial Air Pollution Program Administrators (STAPPA) and Association of Local Air Pollution Control Officials (ALAPCO) have produced a vast amount of data listing a menu of options and their cost characteristics for control of particulate matter (PM), nitrogen oxides (NO_x), and sulfur dioxide (SO_2). They provide a menu of options to assist state and local air-pollution control agencies in identifying and evaluating control options that will help them meet statutory deadlines and attain and maintain the National Ambient Air Quality Standards (NAAQS) for ozone required under Title I of the Clean Air Act Amendments of 1990 (STAPPA and ALAPCO 1994; 1996). They choose a middle path, and not only detail the cost of technology, but also identify specific technologies suitable for specific industry sectors.

1.2.4.2 The Environmental Economics Approach

The environmental economics literature has long recognized the heterogeneity of abatement costs. Examples of heterogeneity in abatement can be found in almost all standard textbooks on environmental economics. Kolstad (2000) has listed the marginal treatment cost of biological oxygen demand (BOD) removal from different sources in a regulatory context (pp 142, cited from Magat et al. 1986). Similarly, Gilpin (2000) has highlighted the variation in pollution control costs according to the choice of the plant, source of energy, and other process characteristics. Typical pollution control costs as a percentage of total plant costs for industries in Europe and North America are shown in Table 1.1. The utility of such a representation of pollution abatement cost without specifying the target pollutants is somewhat limited. Nevertheless, it helps to know the pollution abatement costs as a percentage of total operation cost as it may be helpful in business and policy decisions.

Table 1.1 The Cost of Pollution Control as a Percentage of Total Plant Cost for European and North American Industries

Industry	Pollution Control Cost
Iron and Steel Processing	20%
Non-ferrous Metals	12%
Electricity Generation Plants	10%

Source: Gilpin (2000)

Policymakers, especially in developing countries, do not have enough information about pollution caused by different firms, let alone the cost of abatement for each of these firms. The World Bank developed an industrial pollution projection system (IPPS) based on aggregate pollution intensities of different industry sectors. Martin (1993) has reviewed the IPPS and suggested how it could help policymakers in prioritizing the policies for emission abatement for different sectors. Gupta (2002) has used the IPPS to estimate pollution from various states in India, and identify cost implications of using market-based instruments to reduce emissions. Hartman, Wheeler, and Singh (1994; 1997) examined the pollution abatement costs and expenditure (PACE) survey data for about 20,000 industries and calculated abatement costs for different sectors for a number of air pollutants. In case no information about the pollution load and abatement cost of any industry is available, IPPS could be extremely helpful in prioritizing target sectors for pollution abatement. Although the estimates provided by the IPPS are aggregate and are based on data from the US only, the abatement-cost information can be used in conjunction with actual emission data to design appropriate policy response by using market-based or command-and-control instruments.

Burtraw and Cannon (2000) have explicitly incorporated heterogeneity in abatement costs in a second-best policy setting for environmental protection. They have used a computable general equilibrium framework and concluded that due to heterogeneity of abatement costs, a disaggregate representation of costs results in qualitatively different findings about cost effectiveness of different policies. They have used different MAC functions for different sectors of the economy, namely, transportation, industry, electric (coal), and electric (gas). They find that the emission tax is the most preferred instrument, but that the choice of a policy instrument depends greatly on the percentage reduction from the base level sought. At a 4% level of reduction from the baseline, tradable permits emerge as the cheapest instrument as compared to other non-revenue generating instruments, such as performance standards or technology mandates.

Carlson et al. (2000) analyze the MAC of SO_2 and find that for 678 plants in the US electricity sector, the standard deviation in the abatement cost is three times that of the mean. However, it is not clear if these numbers will apply to other pollutants, such as NO_x, or to other sources.

Newell and Stavins (2003) focus on analysis of the relationship between the nature and magnitude of heterogeneity and prospective cost savings. They recognize the need for a large amount of data to incorporate the heterogeneity of abatement cost appropriately in policy analysis. They propose a rule of thumb that can be employed with a smaller amount of data. It can also be used to conduct an initial screening of policy options for environmental problems. They emphasize the need for policymakers to be able to assess potential cost-savings from the market-based instruments for a particular environmental problem. Their model indicates that the cost savings of market-based policies relative to uniform performance standards increases in proportion to the cost heterogeneity. Heterogeneity in their model results from two sources, difference in the baseline emissions intensities, and difference in the slope of the cost functions.

Although we find a vast amount of data based on fieldwork and surveys from different plants, there is, in general, no theory of heterogeneity of abatement cost in the literature, although such a theoretical framework is available, for example, in understanding heterogeneous technical capabilities of nations and their impacts on competitiveness and trade.

5.2.5 Multi-attribute Tradeoff and Scenario Analysis

Scenario analysis has been used to understand implications of various drivers on the variables of interest. In the corporate world, Shell oil is credited with the use of scenario analysis as a tool to help identify robust strategies to respond to the challenges posed by the first oil-crisis in 1973. Intergovernmental Panel on Climate Change (IPCC) has used scenario analysis to evaluate implications of different greenhouse gas emission scenarios on global climate. Manzini (1999) has used macroeconomic scenarios to evaluate impacts of different energy technologies on the environment in Mexico.

Along with scenario analysis, optimization models have also been among tools of choice to identify optimal solutions to the environmental problems. The classical optimization models aim to minimize cost while meeting one or more environmental constraints. However, many problems, particularly those involving large complex systems, are not amenable to use of the traditional optimization models, either due to the number of often conflicting objectives, or due to lack of a closed analytical form. Moreover, the solution, even if mathematically feasible, may not be economically viable or politically acceptable. Recent developments in the field of optimization, such as multi-objective evolutionary algorithms (for example, see Lumanns 2003), aim to address these issues by using a range of randomized heuristics search algorithms. However, use of the optimization models creates a sense of exclusion and alienation for a large number of stakeholders, because many of them are not familiar with the complex mathematical modeling behind the results. The use of multi-attribute tradeoff analysis lays out the assumptions and quantitatively estimates of various attributes of interests, such as cost, emissions of various pollutants, etc upfront to facilitate the stakeholder participation in the decision process. Therefore, in this study we use this type of scenario analysis. In this method, once the attributes of a set of scenarios are calculated, they are presented to the policymakers and stakeholders, where they can see the implications of changes of one or several alternatives on the outcome or variables of interest. Moreover, the method provides analysts and stakeholders alike with a large set of options to choose from. Even if a solution is not optimal, it may be the second-best, but more acceptable to a wide range of stakeholders and constituents.

Multi-attribute tradeoff analysis has been successfully used by the Analysis Group on Regional Electricity Alternatives (AGREA) of the MIT laboratory for energy and the environment (LFEE) to inform stakeholders and policymakers of implications of various power generation options for the New England region (Connors 2001; Andrews 1992). The method has also been successful in initiating a policy dialogue in long-term power planning in the Shandong province in China (Connors et al. 2003).

1.3 Significance and Relevance of Research

My research makes a significant theoretical contribution to the literature, and has relevance to industrial and environmental policy and regulation.

1.3.1 Contribution to the Literature

My research contributes to the field of environmental management and policy in two ways; first, by cross- application of theories and concepts from different fields, and second, by developing an energy demand and emissions model for the MCMA industrial sectors. The model includes the effects of macroeconomic indicators on industrial growth, end-of-pipe emissions control technologies, structural shift in the industry, fuel-switching, and energy intensity on air emissions. The emissions estimates, coupled with the discounted cash flows (DCF) of capital investments from the model, allow me to conduct the multi-attribute tradeoff analysis and identify cost-effective strategies. Further, the two measures of cost, total capital cost and total policy cost, allow me to analyze the policy implications of different strategies.

The IPAT identity has long been used for delineating the impact of various drivers on energy demand and greenhouse gas emissions. I integrate the shift-share analysis, or the decomposition of energy demand analysis to explicitly include the role of structural shift in the industrial sector, with the IPAT framework to model emissions of five target pollutants of interest, i.e., SO_2, NO_x, hydrocarbons, carbon dioxide (CO_2), and particulate matter smaller than 10 micrometer in size (PM_{10}). Further, I have also included the impact of control technologies and fuel-switching on the emissions. The model can be easily adapted to estimate emissions from industrial sector of any other megacity.

1.3.2 Practical Contribution to Policy Making

Policymakers will benefit from the results, and the analysis presented in this study. First, policymakers can evaluate the costs and the impacts on pollutant emissions, of various targeted emissions reduction policies, either those focusing on reducing the output from the industrial sector by promoting deindustrialization or the ones focusing on increasing penetration of end-of-pipe and process control technologies. The results of the analysis indicate that technology-based solutions alone will not be enough to meet the aggressive air-pollution abatement targets in the MCMA.

Although the industrial sector has been an integral part of the air-quality programs in the past (Molina and Molina 2002), the focus of environmental policy options in the past air-quality programs has been abatement of air pollution by fuel-quality improvements and fuel-switching from industrial diesel to natural gas. There has been no mention of the implications of structural change in the industrial sector, and end-of-pipe controls for industry have not been included. Moreover, the time frame of the air-quality programs has been rather short-term (5 to 10 years). My analysis evaluates implications of various factors on emissions for a 25 year time frame, providing policymakers a handle on a relatively longer-term perspective to deal with industrial air pollution and policy issues.

A quantitative estimate of the potential savings from the use of market-based regulatory instruments (see Chapter 8) can provide a support for creating markets for the implementation of the market-based instruments.

Specifically for the MCMA, I find that the structural shift within the manufacturing sector will be a key driver affecting industrial energy demand and air emissions. Energy planning and policy, and infrastructure development for energy delivery will benefit from the insights on change in the energy demand owing to the structural shift scenarios in the MCMA. This research would also help integrating industrial and environmental policy making in the MCMA.

Finally, the results and analysis presented in this study provide a necessary input to carry out a detailed analysis of the deindustrialization policy initiative and its implications on the job growth and economy in the region.

1.4 Dissertation Outline

In this Chapter, I discussed the motivation for the research, the debate about the role of technology in achieving sustainability, and the impact of technological change in dealing with the environmental problems. I also outline the theoretical basis of my research and policy implications. Chapter 2 deals with the research question, and explains the methodology. In Chapter 3, I portray the industrial and environmental profile of the MCMA. In Chapter 4, I provide an outline of the Future Stories and macroeconomic indicators developed for the scenario analysis. In Chapter 5, I develop the simulation model to estimate energy consumption and emissions from the industrial sources in the MCMA. Chapter 6 deals with the structural shift in the manufacturing sector and estimation of energy demand for the three Future Stories. Implications of changing energy intensity in different sub-sectors are also modeled to estimate industrial energy demand scenarios. Chapter 7 applies the model developed to the MCMA industrial sector and estimates costs and emissions abatement from the industrial sector in the MCMA. The multi-attribute tradeoffs and scenario analysis carried out in this chapter provides insight into suitability of various technology and policy options. In Chapter 8, savings from the application of equimarginal principle to the MCMA manufacturing sectors are estimated. Chapter 9 also reviews policies for air-pollution abatement in Mexico and specifically looks at the feasibility of policy options, and concludes with recommendations.

Chapter 2

Research Question and Methodology

In Chapter 1, I outlined the motivation and rationale for the need to identify cost-effective technology and policy options for reducing industrial air-pollutant emissions in the Mexico City Metropolitan Area (MCMA). I also discussed the theoretical contribution and practical relevance of my research to the policy issues. This chapter outlines the specific questions that my research aims to answer. In Section 2.1 I describe the specific goals of this research. In Section 2.2 I outline the research methodology and steps taken to carry out the research. Section 2.3 discusses sources of error and uncertainty.

2.1 The Research Questions and Goals

The fundamental research question that motivates my research is as follows:

Can technology-based solutions, such as end-of-pipe or process controls, succeed in achieving environmental goals, specifically air-pollution abatement, in the industrial sector of the Mexico City Metropolitan Area (MCMA)?

Several other questions I aim to answer in the process are as follows:

- *What is the impact of structural change in the MCMA manufacturing sector on energy demand and emissions of air pollutants?*
- *How does the rate of change of technology and fuel-switching play a role in achieving air-pollution abatement targets in the MCMA industrial sector?*
- *What is the cost of achieving the emissions reductions for the MCMA industrial sector?*
- *What is the policy cost of implementing air-pollution abatement strategies, including the cost of foregone production due to deindustrialization?*

- *What is the potential for savings from applying market-based flexible mechanisms to achieve the industrial air-pollution abatement goals in the MCMA?*
- *What are the cost-effective policy options to achieve the abatement targets?*
- *Are there any dominant set of solutions that would be robust under any future scenario?*

These specific questions help me to break the task into smaller manageable chunks and provide a direction to my research.

2.2 Research Methodology

To answer the aforementioned questions, I use a research methodology which draws upon several quantitative and qualitative tools, as described in this section.

The first step in any successful research study is to identify the problem and set the system boundaries, in order to be able to manage the problem in the most efficient manner. Broadly, the research question I answer concerns reducing emissions from the industrial sources in the MCMA. However, there could be several ways to look at the problem of industrial air pollution and its implications. For example, how much it would cost to reduce the emissions, or what are its health impacts and policy implications?

I narrow down the scope of the research problem and look at the implications of emissions' scenarios of the industrial production in the MCMA over a 25 year period, from 2000 to 2025. Specifically, I aim to find out if technology related solutions alone, such as deploying end-of-pipe or process controls for NO_x or PM, would be successful in achieving emission reduction goals. After identifying the research problem and sub-problems, I apply the research methodology as described in the following sub-sections.

2.2.1 Developing an Emissions Profile of the MCMA Industrial Sector

First, I define a physical system boundary by identifying the delegations and municipalities included in the definition of the MCMA. Next, I develop a profile of the MCMA and identify the drivers of growth of the city, such as population. The three Future Stories (see Chapter 4 for details of the Future Stories) provide a starting point to identify and quantify the macroeconomic indicators affecting the demand for goods and services by the population in the MCMA over the study period.

Industrial sector provides not only goods and services, but also employment to a large population in the region. I outline the economic role of the industrial sector in the MCMA by quantifying its share in providing employment, and its contribution to the gross regional product.

Industrial emissions are either a result of the manufacturing processes or a product of combustion of fuels. Therefore, data about fuel and energy consumption is important to be able to model emissions. This includes gathering data about the number and types of industries in the MCMA, their fuel consumption, and their emissions of the criteria pollutants resulting from industrial processes or from the combustion of fuels. The industry profile of the MCMA provides a basis to develop a simulation model, in order to conduct the scenario analysis. An emission profile of the MCMA industrial sources is developed on the basis of emissions inventory data for the MCMA, for the years 1998 and 2000. I used the emissions data from the emissions inventory developed by the Metropolitan Environmental Commission (*Comisión Ambiental Metropolitana* or CAM), and in some cases data from the Annual Schedule of Operations (*Cedula de Operación Anual* or COA) is also used to supplement the information about emission controls in the MCMA.

I use the data from the MCMA emissions inventory for 2000 to analyze the role of the industrial sector in the air-pollution problem in the city. The 2000 industrial emissions also serve as baseline emissions for the simulation model.

2.2.2 Energy Demand Scenarios for the MCMA Industry

The next step is to develop scenarios for energy demand in the MCMA. I use the macroeconomic growth rate from the three Future Stories, changes in the energy intensity, and changes in the structure of the MCMA industry -- from low energy intensity to high energy intensity or vice versa -- to estimate energy demand over the study period.

I obtain baseline energy consumption for the MCMA from the Energy Balance (Bazan 2000). For tracing the structural shift in the MCMA industry, I obtained industrial economic output data for industries in the Federal District (*Distrito Federal* or DF) and State of Mexico (*Estado de Mexico* or EM) at a two-digit sub-sector level. Next, I analyzed the structural shift in the industrial sector for DF and EM. Further, I develop an empirical relationship to combine EM and DF data to estimate industrial output from the MCMA[1].

Once the industrial economic output data for the MCMA was estimated, the industrial output was reduced from nine to four sub-sectors to simplify the analysis. Three sub-sectors were chemical, metal products, and food & beverages, and the fourth was the rest of the sub-sectors combined. This reduction is logical as the three sectors combined contribute to about three-fourth of the total industrial output in the metropolitan region.

[1] Since all the municipalities of the EM are not part of the MCMA, the following formula was empirically established for year 1998 and it was used for estimation of output from the MCMA for all the subsequent years. Industrial Output (MCMA) = Industrial Output (DF) + 0.718 * Industrial Output (EM)

The analysis of data for the MCMA from 1995 to 2003 indicated a structural shift from the metal-products sub-sector to the chemical sub-sector. Three possible scenarios to capture this structural shift were modeled to estimate their impact on the industrial energy demand in the MCMA.

2.2.3 Simulation Model for Estimating Industrial Air-Pollutant Emissions in the MCMA

In the next step, I develop a simulation model to incorporate the impact of end-of-pipe, and process control technologies, and technical change[2] to estimate and project emissions of pollutants of interest from the industrial sources of air pollution in the MCMA. Details of the model and parameters used to characterize the end-of-pipe control technologies and technological change, as captured by the model, are discussed in Chapter 5 and Chapter 7.

Industrial activity, fuel consumption, fuel type, energy intensity, end-of-pipe NO_x controls, end-of-pipe particulate matter controls, and operation and maintenance are some of the parameters incorporated in the simulation model. Some of these parameters are a function of the macroeconomic policies and the economic environment in Mexico, and in the MCMA. The interaction of these parameters is captured by taking historical values for these parameters in Mexico and anticipated interactions with macroeconomic indicators, as portrayed in the Future Stories for the MCMA economic and social conditions by Dodder et al. (2004). Details of the parameters and selected values of options for modeling can be found in Chapters 5 and 7.

[2] Capital investment in machines and equipment is used as a proxy for technical change in the MCMA industrial sector.

2.2.4 Coding the Model and Running it for Various Scenarios

I compiled basic data for various parameters, historical emissions and emission factors in an Excel spreadsheet based database. Further I wrote a program to estimate emissions for the Future Stories as well as various parameters. The program was written in Visual Basic for Applications (VBA) to interface with the Excel data-sheets. For each parameter, two or three options were chosen resulting in a total of 749 scenarios for the three Future Stories. The output, emissions, and cost estimates for different years starting in 2000 were stored in Excel spreadsheets, to facilitate analysis.

2.2.5 Identifying a Combination of Effective Strategies and Their Costs

The combinations and permutations of various options for each parameter resulted in a large number of scenarios. Each of the scenarios reflects a unique value for each of the parameters, has a different emission profile and associated capital and total policy cost. To analyze the scenarios, a combination of qualitative and graphical analytical tools and methods were used. Two measures of the cost were used, total capital cost, and total policy cost. The net present value of these cumulative costs was calculated using the discounted cash flow (DCF) for a range of inflation-adjusted discount rates for the three Future Stories.

2.2.6 Estimating Potential Savings Using Market-Based Regulatory Instruments

Market-based instruments claim to achieve emissions reduction targets in an economically efficient manner. To estimate savings from the use of market-based instruments, I use a sectoral approach, as firm level data for abatement-cost curve and emissions were not available. The nine industrial sectors have heterogeneous abatement costs and each sector reduces its emissions such that the marginal-abatement cost of each of the sectors is equal.

I used the sectoral emissions data for two pollutants, PM_{10}, and NO_x from the MCMA emissions inventory. The abatement cost for various sub-sectors was obtained from Hartman et al. (1997). The sub-sectoral abatement cost data is based on econometric estimations of data from the US manufacturing sector. I used the optimization routine Solver® of Microsoft Excel to estimate savings for different levels of abatement, namely, 10% to 50%, in increments of 10%. I also calculated the abatement burden for each sub-sector to achieve emissions reductions cost-efficiently.

2.2.7 Analysis of the Results

Further, I qualitatively selected a group of strategies, which not only covered a wide range of options, but also looked promising in terms of potential for implementation. The criterion used to identify promising strategies was cumulative emissions over the model period, and cost-effectiveness. Tradeoff frontiers were plotted to identify the most cost-effective combination of options. Multi-attribute tradeoff analysis was used to identify the robust strategies for achieving emissions abatement from the industrial sector in the MCMA.

2.3 Sources of Error and Uncertainty

There are several factors in the model that could lead to error and uncertainty in the estimation of energy consumption, emissions, and the cost of abatement. Some of the important ones are discussed in this section and ways to improve upon them are also suggested.

2.3.1 Emissions Inventory

The emissions inventory for the MCMA for year 2000 (SMA 2004) is used as a baseline for emissions estimation by the model. If there is significant error in the baseline emissions data, it will cascade through the complete range of emissions estimations. Two important sources of error and uncertainty in the emissions inventory have been discussed briefly in this section. Sosa et al. (2000) have conducted a detailed analysis of the MCMA emissions inventory for 1998, which sheds light on some of the sources of errors and uncertainty. On the methodology level, some significant improvements have taken place in the recent past (CAM 2001; SMA 2004). Still there are several systemic factors that could affect the emissions estimations.

2.3.1.1 Uncertain Number of Industrial Establishments in the MCMA

The baseline emissions for the model were taken from the emissions inventory. Emissions inventory for the MCMA does not include emissions from all the industrial establishments in the MCMA. The 1998 emissions inventory for the MCMA reports emissions from only 6200 large industrial sources, whereas the 2000 emissions inventory reports data from even fewer industrial sources. The Mexican national geographical and economic information institute (INEGI) conducted a census of industries in 1999. According to the INEGI data, in 1998 there were more than 61,000 establishments in the MCMA.

It is possible that the emissions from the unreported sources are very small, however, the discrepancy in the data may result in a systematic under-reporting and therefore, a bias in the results.

2.3.1.2 Error in the Estimation of Emissions

There are very few industries in the MCMA that have any continuous emissions monitoring equipment installed. Most of the data reported in the emissions inventory uses one of the following three methods: engineering estimates, mass balance, emission factors, or a combination thereof. For certain pollutants like NO_x, the estimates of emissions could have large uncertainty, as the NO_x emissions are dependent on combustion process and temperature. Moreover, the firms in the MCMA have to comply with the official norms for emissions from the combustion sources. Given the low-level of monitoring, verification, and enforcement, firms have incentives to report emissions within the norms to avoid scrutiny or penalties. This could also result in under-reporting of emissions data.

2.3.2 Energy Intensity of the MCMA Industrial Sub-sectors

Energy intensity data at the sub-sector level are not available for the MCMA. I used corresponding sub-sector energy intensity data from the US manufacturing sector and calibrated the same to estimate the MCMA sub-sector energy intensity. The structural differences in the MCMA and the US manufacturing sub-sectors, such as the degree of automation or differences in the product-mix, could mean that this would introduce a bias in the MCMA sub-sector energy intensity estimation. However, it is difficult to predict the direction of this bias. A sub-sector level data collection about energy consumption for the MCMA could possibly help eliminate this source of error and uncertainty.

2.3.3 Uncertainties in the Cost Estimations

Estimating cost was one of the most challenging tasks. Data about the cost of end-of-pipe controls for NO_x, PM, and capital stock turnover for the MCMA industry were not available. Also, the policy cost is modeled as only the cost of foregone industrial output and does not include the secondary impacts on employment and demand for intermediate goods.

2.3.3.1 End-of-pipe Controls and Capital Stock Turnover

As per the data base of annual schedule of operation (*cedula de operación* or COA), there are no end-of-pipe or process NO_x controls installed in the manufacturing sector in the MCMA. Therefore, MCMA specific cost data for NO_x controls was not available. Although COA reports installation of a few PM control equipment, I have used the cost data from the US installations. One could argue that the NO_x control equipment is manufactured by multinational corporations, and their cost around the world will be more-or-less same unless they are locally invented and manufactured in Mexico. However, there still remain differences in the operation and maintenance costs, which in the long run could be very different for Mexico and for the US. For PM controls, the difference in the US and Mexican data could be significant, and this could have led to over estimation of the cost of PM control in Mexico. By conducting a survey of the MCMA manufacturers, the local PM control costs can be estimated. This can be done by making pollution abatement and cost expenditures (PACE) to be a part of the annual industrial survey or industrial census.

There are no data sources that I could find which provided – in general – how much investment in upgrading machines and equipment by the industry would result in what change in the energy intensity of the industry. As discussed in Chapter 7, some research for particular industries, such as steel mills in the US is available, but this can not be applied to all the industries in the MCMA. Therefore, I used an ad hoc correlation between the R&D investment and changes in the energy intensity from the model developed by Wing (2001) in the context of global climate change, and estimated a linear relationship between capital-stock turnover and changes in the energy intensity, and calibrated it for the MCMA industry. Moreover, targeted policy-initiated capital-stock turnover (with an objective to reduce energy intensity) and the business-as-usual capital-stock turnover rate would have a different effect on the rate of change of energy intensity. The capital-stock turnover estimates for reducing energy intensity do not take this difference into account.

2.3.3.2 The Policy Cost

The policy cost as modeled in this study, not only includes the direct control costs, but also includes the cost of foregone industrial production, as a result of a policy to induce deindustrialization in the region. However, reduction in the industrial output will also reduce the demand for intermediate goods and services, which have not been accounted for, due to lack of availability of an input-output model or framework for the MCMA. Moreover, the reduction in output will also affect the local level of employment, which has not been included in the policy cost. It is assumed that the policy to reduce emissions by deindustrialization will be employment-neutral, which may not be the case in reality. One way in which deindustrialization can be employment neutral is by shifting the structure of the economy from manufacturing to services. However, the productivity of the manufacturing and service sectors is different and could lead to differences in level of employment.

2.3.4 Other Sources of Error and Uncertainty

Predicting the future is a risky business. The Future Stories (see Chapter 4) are an effort to get around this problem by crafting a wide range of consistent scenarios and weaving them in the form of Future Stories. However, initial data suggest that there are serious discrepancies between the way the human mind thinks and the actual world works. For example, none of the three Future Stories estimations of growth rate for the MCMA industries come close to the actual decline in growth witnessed in the years 2000 through 2003. The stochastic nature of the growth and macroeconomic indicators has been addressed to some degree by introducing a random error and simulating the exogenous growth in industry about a mean value.

In spite of the above mentioned sources of error and uncertainty, the range of scenarios cover a wide range and the model is able to predict general trends which should provide useful insights to the policymakers in designing energy, environmental, and industrial policies for the MCMA.

In this chapter, I specified the research questions that my research aims to answer, and outlined research steps, data sources and discussed sources of error and uncertainty. In the next chapter, I lay the groundwork for my research and analysis. I define the system boundary and outline the basic information about the air pollution in the Mexico City Metropolitan Area.

Chapter 3

A Profile of the MCMA: Economy, Air Pollution, and the Industry

Chapter 2 described the specific research questions and research methodology. This chapter lays the groundwork for application of the methodology and analysis in the subsequent chapters. First, I define the region studied in this research, the Mexico City Metropolitan Area (MCMA) and describe its salient characteristics, such as population and topography. Later, I delineate the air-pollution problem in the MCMA and use the data from the emissions inventory to highlight the role of industry in the MCMA air-pollution problem.

3.1 The Mexico City Metropolitan Area : Defining the System Boundary

A clear definition of the system boundary is essential for the research results to be reproducible. In this section, I specify the delegations and municipalities of the Federal District (*Distrito Federal* or DF) and the State of Mexico (*Estado de Mexico* or EM), which define the boundary of the MCMA as used in this research.

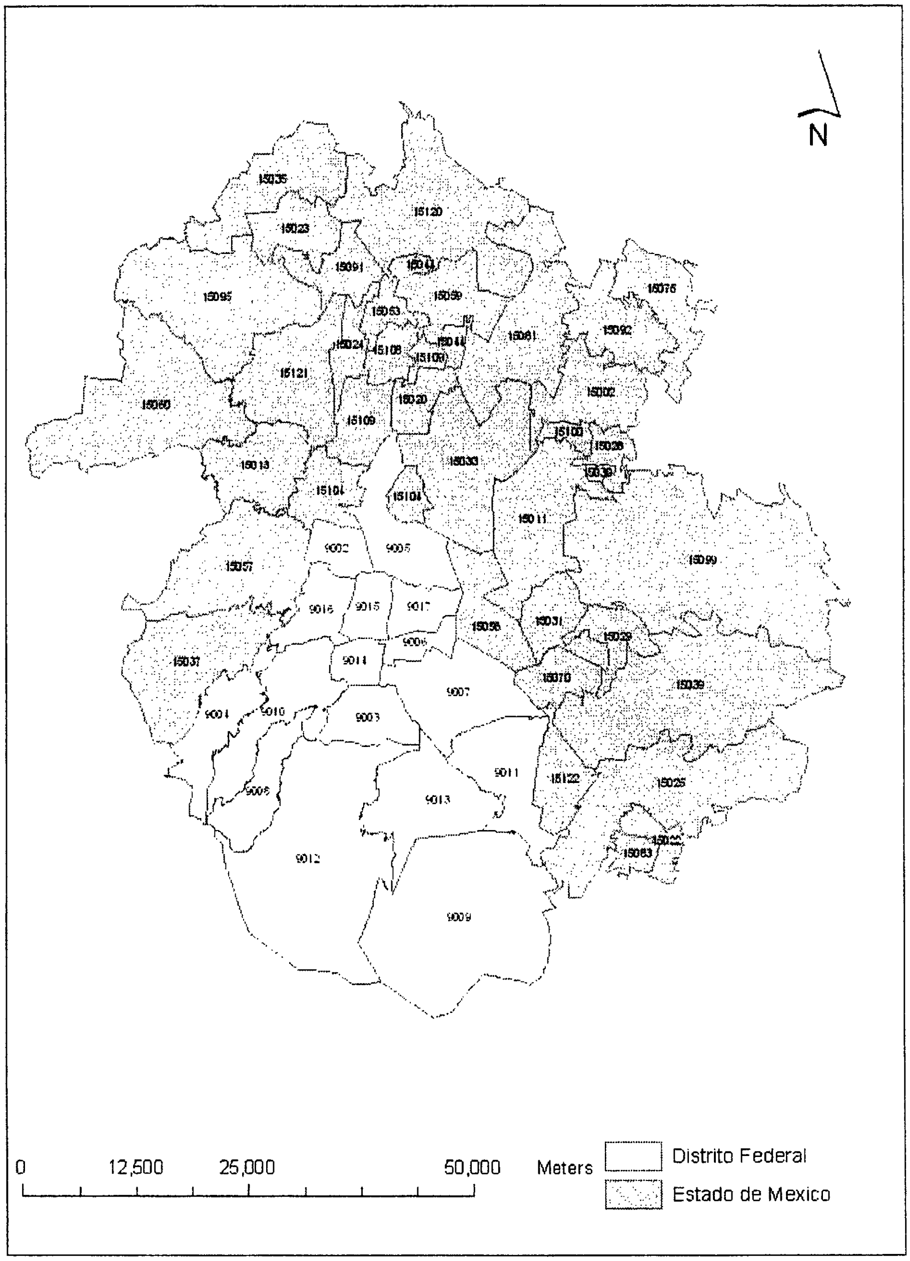
The MCMA is the hub of economic, political, and industrial activity in Mexico (Molina and Molina 2002). It has been growing in size and population. As a result of continued urban growth, the definition of the MCMA is dynamic and has been changing over time. As per the currently accepted definition (for a detailed discussion, see Aoki 2002; Molina and Molina 2002; Dodder 2003) of the MCMA, it consists of all the 16 delegations (*delegaciones*) of the Federal District and several contiguous municipalities (*municipios)* of the State of Mexico. The emissions inventory for the year 2000 for the MCMA, also known as the *Zona Metropolitana del Valle de Mexico* (ZMVM) includes only 16 contiguous municipalities from the State of Mexico in the definition of the MCMA (SMA 2004). However, several other municipalities in the State of Mexico are rapidly growing and are becoming an integral part of the economic activity in the region. In this study, I use the broader definition of the MCMA, unless otherwise specified, used in Molina and Molina (2002). It includes the 16 delegations from the DF and 37 contiguous municipalities from the EM. A map of the MCMA with the included delegations and municipalities is show in Figure 3.1. The corresponding list of the delegations and municipalities is given in Table 3.1.

3.1.1 Population and Topography of the MCMA

According to the 2000 census (latest available) data, the population of the MCMA was 18 million, which is 18% of the total population of Mexico (INEGI 2003). The DF had over 8.6 million inhabitants in 2000 and the overall rate of population growth in the DF was declining (Molina and Molina 2002). In the same year, population of the EM was 13 million, and in the urbanized part of the EM (the 37 *municipios* included in the definition of the MCMA) the number of inhabitants was 9.2 million. The population density of the MCMA is higher than that of many other megacities in the world. It was 9,875 persons per square kilometre (Dodder 2003) in 2000. Figure 3.2 shows population and population-density trends in the MCMA. The notable decline in the population density (1980-1990) is due to change in the definition of the MCMA, thereby changing the area of the MCMA. The population density in the delegations and municipalities of the MCMA in 2000 is shown in Figure 3.3.

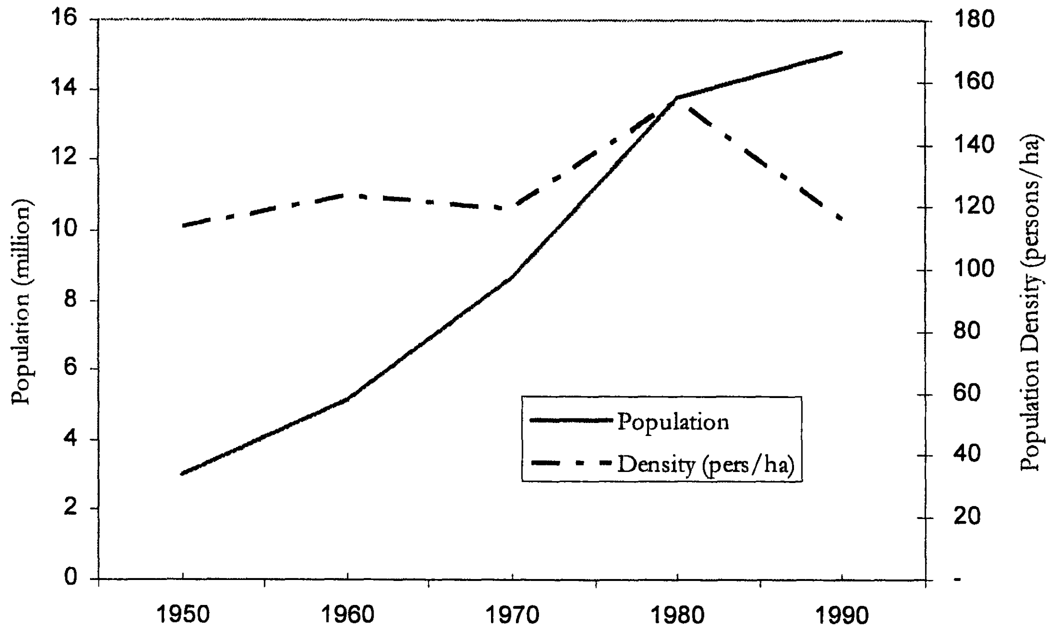
Note that the population density in the centre of the MCMA is the highest. Along with population density, Figure 3.4 shows density of industrial establishments. The figure indicates that the MCMA industrial establishments are concentrated in the densely populated areas of the region.

Figure 3.1 The Delegations and Municipalities in the MCMA



Source: Based on data from INEGI (2004)

Figure 3.2 Population Growth and Population Density Trends in the MCMA



Source: Dodder 2004

The MCMA is situated in a basin at an elevation of 2,240 meters above the mean sea level. The floor of the basin is almost flat. It is confined on the east, west and south sides by mountain ridges; the valley has a wide opening to the north. High altitude, subtropical latitude, photochemistry, and pollutant emissions in the MCMA are conducive to formation of ground-level ozone throughout the year, except during the wet summer months (Molina and Molina 2002).

3.1.2 Economic Activity in the MCMA

The MCMA is the hub of the Mexican economy. A large number of industries and financial institutions are located in the region. Lezama et al. (2002) predict, "Evolution of economic growth will be a key variable for the elaboration of scenarios concerning air quality trends." The manufacturing sector and the commercial and

Table 3.1 List of the Municipalities (EM) and the Delegations (DF) in the MCMA

Federal District (DF)		The State of Mexico (EM)			
Code	**Delegacion**	**Code**	**Municipio**	**Code**	**Municipio**
9002	Azcapotzalco	15002	Acolman	15057	Naucalpan de juarez
9003	Coyoacan	15011	Atenco	15058	Nezahualcoyotl
9004	Cuajimalpa de morelos	15013	Atizapan de zaragoza	15059	Nextlalpan
9005	Gustavo a. madero	15020	Coacalco de berriozabal	15060	Nicolas romero
9006	Iztacalco	15022	Cocotitlan	15070	Paz, la
9007	Iztapalapa	15023	Coyotepec	15075	San martin de las piramides
9008	Magdalena contreras, la	15024	Cuautitlan	15081	Tecamac
9009	Milpa alta	15025	Chalco	15083	Temamatla
9010	Alvaro obregon	15028	Chiautla	15091	Teoloyucan
9011	Tlahuac	15029	Chicoloapan	15092	Teotihuacan
9012	Tlalpan	15030	Chiconcuac	15095	Tepotzotlan
9013	Xochimilco	15031	Chimalhuacan	15099	Texcoco
9014	Benito juarez	15033	Ecatepec	15100	Tezoyuca
9015	Cuauhtemoc	15035	Huehuetoca	15104	Tlalnepantla de baz
9016	Miguel hidalgo	15037	Huixquilucan	15108	Tultepec
9017	Venustiano carranza	15039	Ixtapaluca	15109	Tultitlan
		15044	Jaltenco	15120	Zumpango
		15053	Melchor ocampo	15121	Cuautitlan izcalli
				15122	Valle de chalco solidaridad

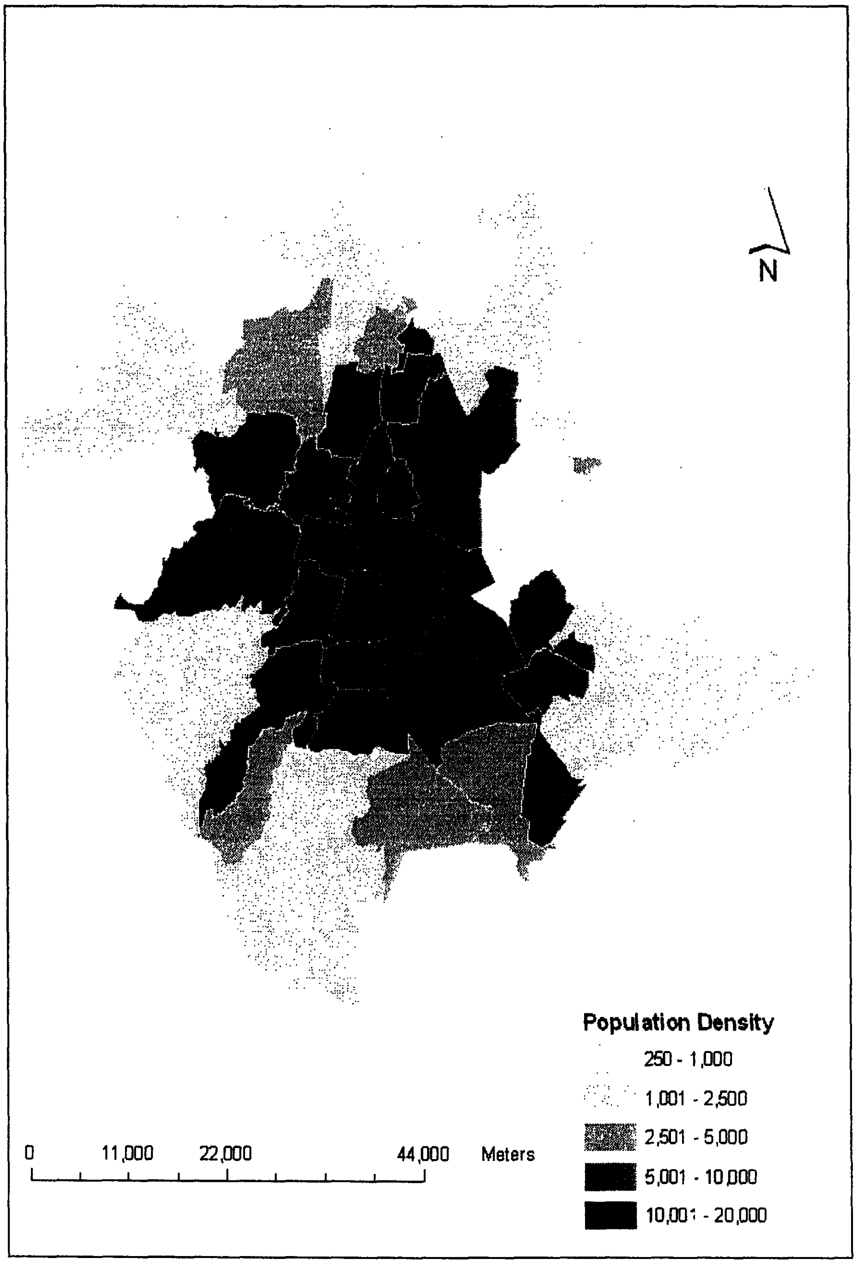
Source: Molina and Molina (2002); Dodder et al. (2004); INEGI (2004)

service sector are the main contributors to the gross regional product (GRP) in the MCMA.

3.1.2.1 The Industrial Sector in the MCMA

The manufacturing sector in the MCMA contributes about one-third of the total manufacturing output in Mexico. In the year 2000, the manufacturing sector in the MCMA produced goods worth 400 billion pesos (INEGI 2003). With the signing of NAFTA in 1994 and setting up of export-oriented manufacturing facilities on the border region, the share of theoutput from the MCMA manufacturing sector in the national economy has decreased. Many pollution intensive industries have migrated from the DF to the neighboring State of Mexico, or to the industrial corridor on the US-Mexico border region. As a result of the above two factors, the overall contribution of the manufacturing sector in the MCMA economy has decreased (Molina and Molina 2002).

Figure 3.3 Population Density in the Delegations and Municipalities of the MCMA



According to the 1999 economic census (INEGI 2003) in 1998 there were 56,430 economic establishments in the MCMA manufacturing sector, which contributed 400 billions of Mexican pesos (on a value added basis) to the regional economy. The role of the manufacturing sector in the air pollution is discussed in section 3.3. The characteristics of the MCMA manufacturing sector, its structure, and its role in the economy are discussed in detail in Chapter 7.

3.1.2.2 The Commercial, Informal, and Services Sectors

The commercial and informal sector is an important part of the MCMA economy. According to some estimates, the commercial and informal sector provides about 70% of the employment in the region and about 53% of the employment in the nation (Flores 2004). The commercial sector has been growing in the MCMA at the expense of the shrinking industrial sector. The emissions inventory for the MCMA recognizes the importance of the commercial and informal sector, and includes specific sub-sectors such as bakeries, dry cleaners, printing and graphic arts under the category of area sources. As per the definition used by the Mexican National Institute of Statistics, Geography and Informatics (*Instituto National de Estadística Geografía e Informática* or INEGI), the informal sector is a set of economic establishments dedicated to the production of goods and services. Their main benefit to the economy is the generation of employment and income. The informal sector is characterized by a low level of organization. A basic or no division between labor and capital as factors of production is a hallmark of this sector. Most of the units operating in the informal sector of the economy are unregistered and therefore difficult to track and regulate. However, since they engage in production activities at a small scale, often they are energy inefficient, leading to higher pollution for a given unit of output. Flores (2004) has analyzed various scenarios of growth for the commercial and informal sector in the MCMA and proposed options and strategies to reduce emissions from this sector.

3.2 Air Pollution in the Mexico City Metropolitan Area

The Mexico City Metropolitan Area is one of the largest megacities in the world. It has more than 18 million inhabitants (Molina and Molina 2002; WDI 2003). A list of ten megacities and their latest air-pollution data available is presented in Table 3.2.

Pollution levels in the MCMA have been reported to often exceed the Mexican national ambient air-quality standards. The six criteria air pollutants recognized by the MCMA's metropolitan environmental commission (*Comisión Ambiental Metropolitana* or CAM), are CO, NO_x, PM_{10}, SO_2, lead and ozone. The Mexican air quality standards for air pollutants are listed in Table 3.3.

The air quality standards and peak concentrations of the pollutants in the MCMA are given in Table 3.4. Primarily, emissions from the transportation sector are responsible for the severity of air pollution in the MCMA. The emissions from industrial sources are also a significant contributor to the poor air quality in the MCMA. Industrial sources of air pollution in the MCMA contribute about 13.6% of the annual NO_x emissions, 26% of the anthropogenic particulate matter of size smaller than 10 microns (PM_{10}), and 50% of the total SO_2 emissions. Emissions of CO mainly come from automobiles; hydrocarbon emissions from industry are also small as compared to the emissions from households and other area sources (CAM 2001). Figure 3.3 depicts the contribution of different sources of air pollution in the MCMA.

Table 3.2 Air Pollution in the Megacities[a] of the World

City[b]	Population (Thousands) **2000**	TSP (Micrograms per cubic meter) **1999[c]**	SO_2 (Micrograms per cubic meter) **1998[d]**	NOx (Micrograms per cubic meter) **1998[d]**
New York, USA	20,951	23	26	**79**
Mexco City, Mexico	18,017	69	**74**	**130**
Los Angeles, USA	16,195	38	9	**74**
Mumbai, India	15,797	79	33	39
Calcutta, India	13,822	**153**	49	34
Tokyo, Japan	12,483	43	18	**68**
Jakarta, Indonesia	11,018	**103**	..	..
Osaka, Japan	11,013	39	19	**63**
Delhi, India	10,558	**187**	24	41
Manila, Philipines	10,432	60	33	..
Shanghai, China	10,367	87	**53**	**73**
São Paulo, Brazil	9,984	46	43	**83**
Beijing, China	9,302	**106**	**90**	**122**
Cairo, Egypt	7,941	**178**	**69**	..
Rio de Janeiro, Brazil	5,902	40	**129**	..

a. Megacities – refer to urban agglomerations having more than 10 million inhabitants. Definition source: http://www.doc.mmu.ac.uk/aric/eae/Air_Quality/Older/Megacities.html

b. City population is the number of residents of the city as defined by national authorities and reported to the United Nations. Mostly, the city refers to urban agglomerations.

c. Data are for the most recent year available, most are for 1999.

d. Data are for the most recent year available n 1990–98. Most are for 1995.

Notes:
1. TSP = Total Suspended Particulates
2. The data in bold indicates that it exceeds the WHO norm of 90, 50, and 50 mcrograms per cubic meter, for TSP, Sox and NOx respectively.

.. = No data or insufficient data.

Source: World Development Indicators (2003), Published by the World Bank, pp. 168-169.

Table 3.3 Air Quality Standards for Air Pollutants in Mexico

Pollutant	Exposure (Concentration and Time)	Source of Official Norm
Ozone (O_3)	0.11 ppm (1 hr) (216 $\mu g/m^3$)	NOM-020-SSA1-1993
Carbon monoxide (CO)	11 ppm (1 hr) (12595 $\mu g/m^3$)	NOM-021-SSA1-1993
Sulfur dioxide (SO_2)	0.13 ppm (24 hr) (341 $\mu g/m^3$)	NOM-022-SSA1-1993
Nitrogen dioxide (NO_2)	0.21 ppm (1 hr) (395 $\mu g/m^3$)	NOM-023-SSA1-1993
TSP	260 $\mu g/m^3$ (24 hr)	NOM-024-SSA1-1993
PM_{10}	150 $\mu g/m^3$ (24 hr)	NOM-025-SSA1-1993

Notes:
TSP = Total suspended particles
PM_{10} = Particles less than 10 micrometer in diameter
ppm = parts per million
$\mu g/m^3$ = microgram per meter cube

Source: INE (2000)

Table 3.4 Standards and Peak Concentrations of Criteria Pollutants in the MCMA from Five Measurement Stations

	CO (ppm)	NO_x (ppm)	SO_2 (ppm)	O_3 (ppm)	PM_{10} ($\mu g/m^3$)
Standard (Duration)	11 (8 hr)	0.21 (1 hr)	0.13 (24 hr)	0.11 (1 hr)	150 (24 hr)
1988	29.5	0.327	0.183	0.405	NA
1991	15.9	0.370	0.192	0.404	NA
1995	14.9	0.296	0.081	0.349	241
1997	9.8	0.274	0.099	0.309	324
1999	12.1	0.216	0.094	0.311	184

MCMA = Mexico City Metropolitan Area
$\mu g/m^3$ = microgram per meter cube
ppm = parts per million
NA = Not Available

Source: INE (2000)

NO_x and PM_{10} are the chief target pollutants for devising mitigation strategies from the industrial sector due to their relatively large contribution. They are also important to control from a health perspective, as NO_x is an important ozone precursor, and PM_{10} is associated with mortality and morbidity. NO_x is also responsible for the formation of small secondary particles smaller than 2.5 micrometer in diameter ($PM_{2.5}$), which are considered responsible for increases in mortality (Evans et al. 2002). Combustion of fossil fuels, primarily for generating process heat and for other industrial applications, produces thermal NO_x. Fossil fuel combustion and industrial processes result in the emissions of PM. Industry is also a major contributor (54% of total SO_2 emissions) to the SO_2 emissions in the valley, but the SO_2 emissions are primarily dependent on the sulfur content of the fuel, and the concentration is within norms. However, SO_2 emissions, like NO_x, are a precursor to the formulation of secondary particulate matter (Sosa et al. 2001). Concentrations for ground-level ozone exceeded the standards on a frequent basis in the MCMA. Formation of ozone is a result of complex photochemistry and is affected by the atypical topography of the MCMA, which makes it susceptible to thermal inversions and overnight trapping of pollutants in the valley. There is uncertainty about the precise role the balance of NO_x and hydrocarbons play in the formation of the ground-level ozone, but both are primary precursors of ozone formation (Molina and Molina 2002).

3.3 The Anthropogenic Sources of Air Pollution in the MCMA

Primarily the sources of air pollution in the MCMA are categorized as mobile, stationary (point and area sources), and natural sources. Mobile sources consist of trucks, buses, private and public automobiles, motorcycles, and other means of personal transportation. Stationary sources consist of industrial sources, the commercial and informal sectors, and the residential sector. Natural sources of emissions are vegetation, dust, etc.

3.3.1 The Mobile Sources of Air Pollution in the MCMA

The contribution of emissions from transportation and industrial sources is listed in Table 3.5. Transportation sources are understood to be responsible for the major component of air pollution in the MCMA; they contribute over half of the PM_{10} emissions, about one-third of total SO_2 emissions, over three-fourth of total NO_x emissions, and almost all of the CO emissions. Several other researchers have done scenario analysis of the transportation sources and analyzed abatement options. Aoki (2002) has conducted scenario analysis of the private auto sector in the MCMA. Aoki also investigates the role of technology transfer in the auto sector in Mexico, and concludes that environmental technological change in the Mexican auto sector is influenced by external factors, and the environmental policy is a necessary but not sufficient factor to induce environmental technological change in Mexico. Gilat (2002) has advocated transit oriented development (TOD) and presented implications of promoting the metro in the MCMA. Benbarka (2001), Mostashari (2003) and Bracamontes (2003) have modeled and analyzed the role of buses and diesel trucks in the MCMA air pollution. Dodder (2004) reflects on the MCMA transportation system as a large complex system and explores the role of policy making in dealing with the air-pollution problem in the MCMA.

Table 3.5 Air-pollution Source Categories in the MCMA (2000)

Pollutant / **Source Category**	**PM_{10}** (t/y)	**SO_2** (t/y)	**CO** (t/y)	**NO_X** [1] (t/y)	**TOC** [2] (t/y)
Industry and Power	3,001	10,303	12,125	27,241	23,071
Soil and Vegetation	1,736	N/A	N/A	859	15,425
Mobile Sources	5,287	4,348	2,018,788	157,239	210,816
Area Sources	317	30	4,512	8,112	418,309
Total	**10,341**	**14,681**	**2,035,425**	**193,451**	**667,621**

N/A = Not applicable or Not available

[1] Expressed as NO_2;

[2] TOC = Total Organic Compounds

t/y = tonne/year

Source: MCMA Emissions Inventory (2000) - (SMA 2004)

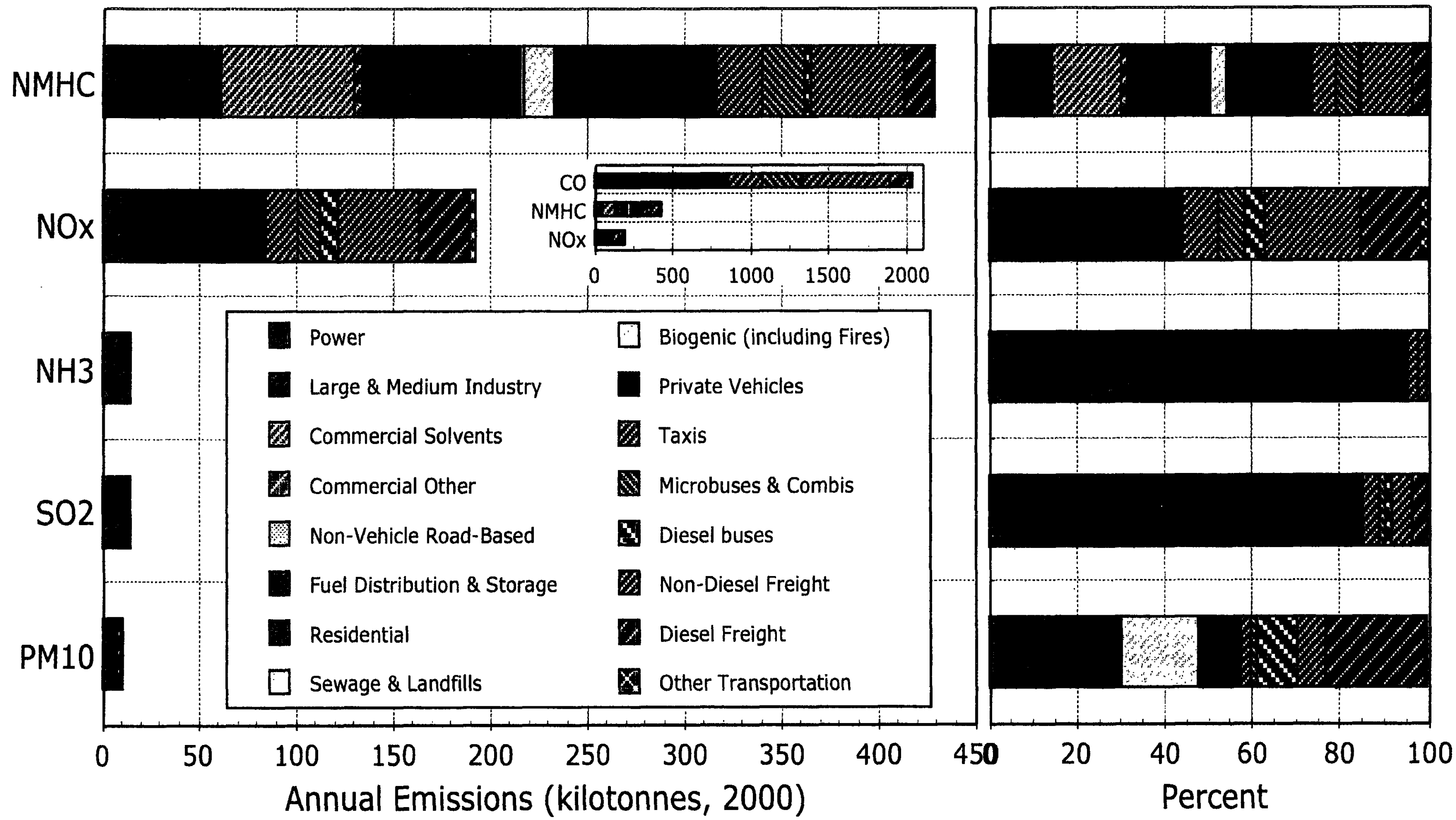
3.3.2 The Stationary Sources of Air Pollution in the MCMA

Industries, the residential sector, and the commercial and informal sector are the other anthropogenic sources of air pollution in the MCMA. The industrial and power sector is a significant contributor to the MCMA air pollutant emissions inventory. They contribute 29% of the total PM_{10} emissions, 74% of the total SO_2 emissions, and 14% of the total NO_x emissions in the MCMA (Table 3.3; Figure 3.4).

Flores (2004) has estimated emissions from the informal sector in the MCMA and analyzed various abatement options. Roth (2003) has conducted a detailed survey of the residential sector to assess energy use in the residential sector and estimated resulting emissions. In this study, I focus on modeling emissions from industrial sources, and use a simulation model to incorporate structural change, technology, and technical change in order to show these changes could affect energy demand and emissions for the period 2000-2025.

The following section describes the role of the industrial sector in the MCMA economy and its contribution to the air-pollution inventory. Although the power generation sector is included in the point source category, along with industries in the emissions inventory, I have not included power generation in the industrial sector, due to its unique nature and non-tangible production. The industrial sector, as considered in this study, consists of facilities engaged in the manufacturing of intermediate or final goods. The process and product manufacturing facilities fall in this category.

Figure 3.4 Emissions Inventory in the MCMA (2000)



Source: Connors 2004; Based on Emissions Inventory Data from SMA (2004)

3.3.2.1 Emissions from Power Generation in the MCMA

There are five power plants in the MCMA. Two power plants are base load units and the other three provide generation capacity for emergency, and for meeting peak load demand. They meet about 1/5 of the total MCMA electricity demand.

The two main generation units are Jorge Luque and Valle de Mexico, with installed generation capacity of 224 and 750MW respectively. Jorge Luqe has four relatively small generation units, 2x32 MW, and 2x80 MW. Valle de Mexico, on the other hand has relatively larger size units, 3x150 MW and 1x300 MW. In the past, both of these power plants were using heavy fuel-oil, high in sulfur content. All the units of both the power plants now use natural gas as fuel in the conventional Rankine cycle configuration to generate steam to produce electricity.

Both the plants were emitting high level of NO_x and were required to take measures to curb NO_x emissions. Jorge Luque plant installed a low-NO_x burner to comply with official norm (110 ppmV at 5% O_2 level) to reduce emissions of NO_x. Three units of Valle de Mexico had NOx emissions within the prescribed norms, whereas the fourth unit (300 MW) NOx emissions were much higher than the official standard.

The fourth unit of the Valle de Mexico has been converted to a combined-cycle plant by installing a topping cycle gas-turbine unit of 249 MW. Presumably, the combustion in the gas turbine unit is much more efficient in terms of NO_x emissions. Although the NO_x emissions from the power generation in the MCMA have significantly reduced as a result of fuel-switching, and repowering of the fourth unit of Valle de Mexico. Repowering of the remaining seven units present an additional potential to reduce NO_x. In the 2000 emissions inventory, NO_x emissions from power generation sector contributed 4% of the total NO_x emissions in the MCMA.

Figure 3.5 The Source Distribution of NO_x Emissions in the MCMA (2000)

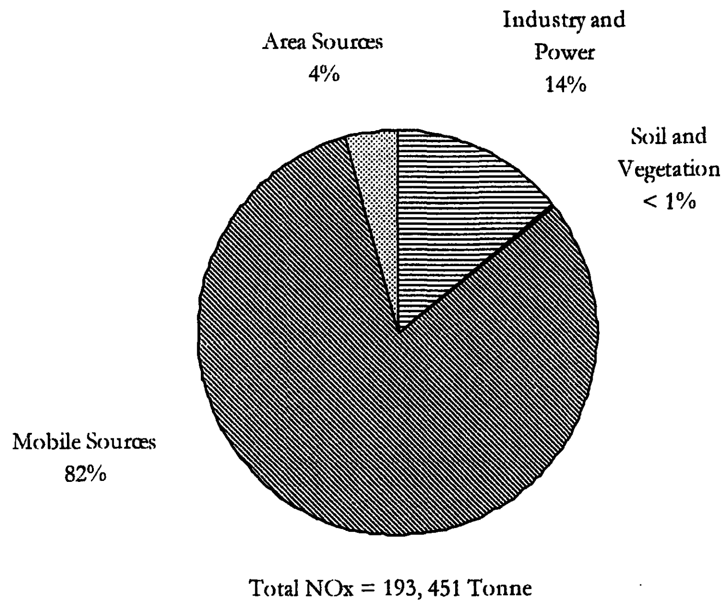
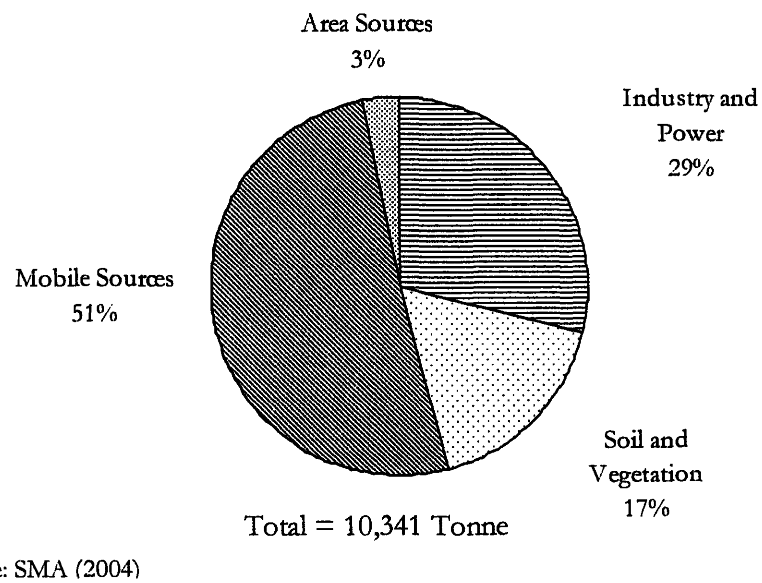


Figure 3.6 The Source Distribution of PM_{10} Emissions in the MCMA (2000)



Source: SMA (2004)

3.4 The Industrial[1] Sources of Air Pollution in the MCMA

With about one-fifth of the Mexico's population concentrated in the MCMA, its industrial sector plays an important role in the regional and national economy and is a large employer in the metropolitan area. It also contributes significantly to the national and regional domestic product. About one-fifth of the total regional economic output is attributed to the industrial sector in the MCMA (Dodder 2003).

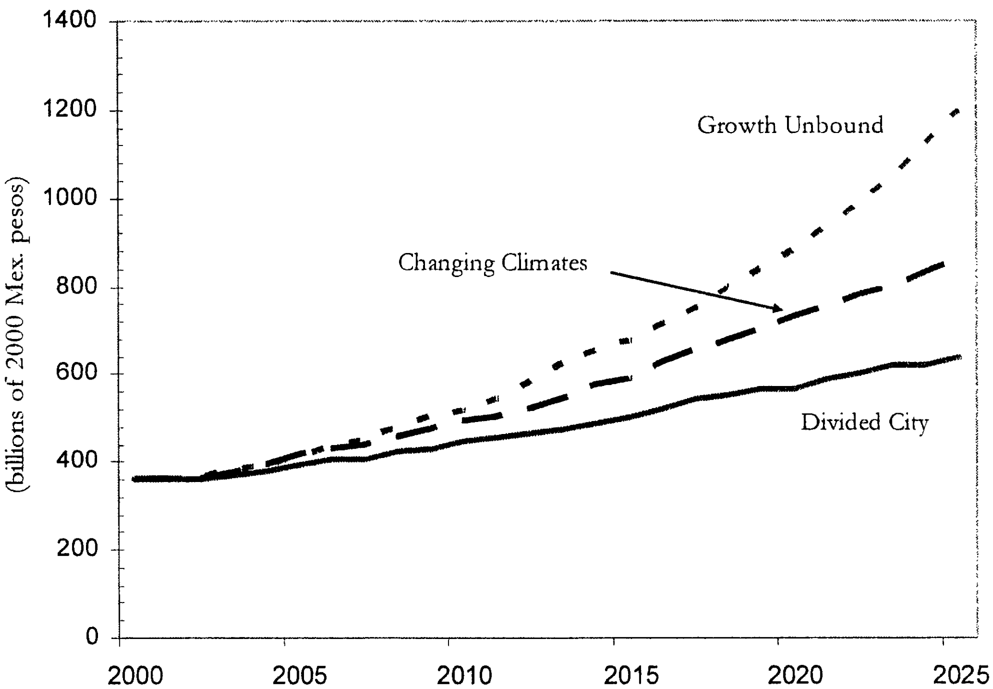
Dodder et al. (2004) has created three Future Stories to portray the dynamics of various macroeconomic and socio-political factors under various growth scenarios. The three Future Stories, Divided City, Changing Climates, and Growth Unbound capture the interactions of a range of macroeconomic and socio-political indicators. These scenarios are discussed in details in Chapter 4.

Figure 3.7 depicts the growth of output from the manufacturing sector in the MCMA under the three Future Stories. In the Divided City scenario, the output from the manufacturing sector in the MCMA is expected to increase by more than 70% from 2000 levels over a period of 25 years. In the Changing Climates scenario the industrial output is expected to grow by about 140% and in Growth Unbound, it is estimated to increase by more than 200%.

The rate of output growth in the MCMA is expected to be slower than that of Mexico as a whole. Historically, the metropolitan area has remained at the forefront of all economic activity, including manufacturing. This dominant role of the MCMA in the manufacturing has changed since the establishment of new export oriented industries on the US-Mexico border area, as a result of growth spurred by the

[1] The terms industrial sector and manufacturing sector are used interchangeably throughout this study. Both refer to the nine industry sub-sectors as defined by the Mexican standard industrial classification.

Figure 3.7 The Growth of Industrial Economic Output in the MCMA (2000-2025)

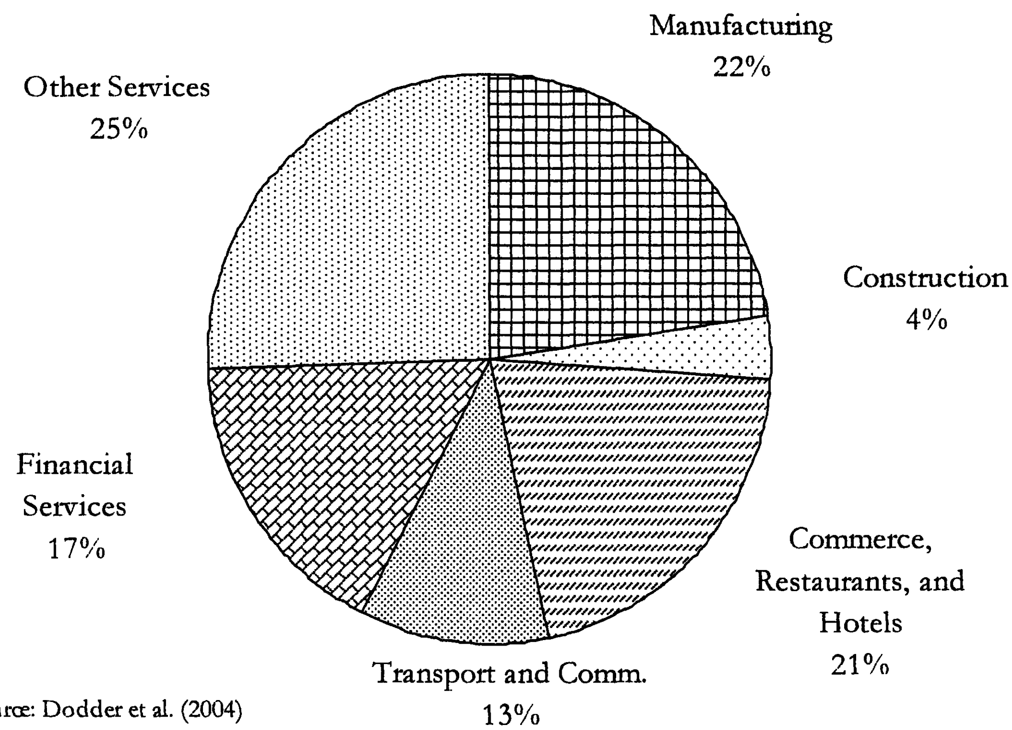


Source: Dodder (2003)

implementation of NAFTA. Moreover, a shift of the metropolitan economy from the industrial to the service sector also has played a key role in determining the growth rate of industries in the MCMA. Among other things, increasing environmental concerns may also have resulted in the slower growth of the industrial sector within the MCMA. Figure 3.8 depicts the share of the manufacturing sector in the MCMA's gross regional product (GRP) in 1998. In the sectors shown, manufacturing sector contributed 22% to the total regional output in 1998, second only to the other service sector, which contributed 25% (Figure 3.8). Commerce, restaurant and hotels are also a large contributor to the regional economy.

In the Changing Climates scenario, the relative contribution of the manufacturing sector to the total regional output is expected to remain stable, whereas in the case of the Divided City scenario, its share of the manufacturing activity is expected to rise slightly. In the Growth Unbound scenario, the manufacturing sector is expected to increase its contribution to the regional economy from current levels of 23% to about 26% in 2025.

Figure 3.8 The Share of Economic Sectors in the Total Economic Output of the MCMA (2000)



Source: Dodder et al. (2004)

Note: Following sectors contribute less than 1%, and have not been included in the chart: Mining, Agriculture, Electricity and Water

Everything else remaining same, the range of increase in the output from 70% in the Divided City to over 200% in the Growth Unbound scenario over a period of 25 years would mean a significant increase in air-pollution from the industrial sector. Therefore, it is important to examine the roles of various parameters that affect the emissions trajectory from the industrial sector in the MCMA, in order to design effective abatement strategies.

3.4.1 Industrial Establishments in the MCMA

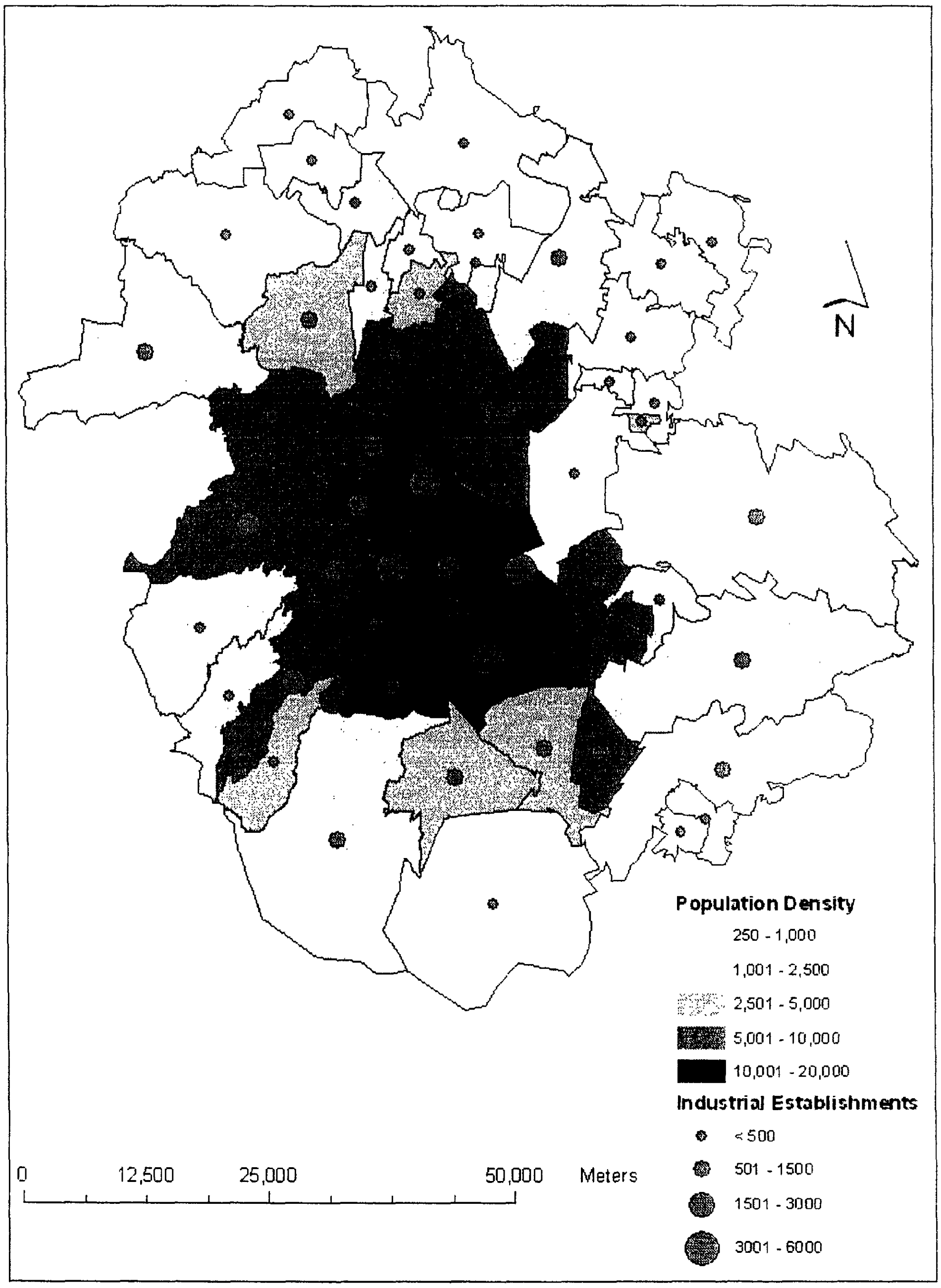
The manufacturing sector in the MCMA consists of industrial establishments in the DF and in the State of Mexico. According to INEGI, the total number of industrial establishments in the MCMA[2] in 1998 was over 31,000 (cited in CAM 2001), of which about 60% were located in the DF and the rest in the municipalities of the EM that are part of the MCMA. The 1999 economic census document of INEGI reports more than 56,000 establishments in the manufacturing sector in the MCMA (INEGI 2003).

Although, the number of industrial establishments in the MCMA is reported to be over 31,000, only 6,280 industrial establishments are accounted for in the emissions inventory for the year 1998 (CAM 2001). Presumably, only the large and medium size industries, as well as those that are required to report their activities annually in the annual schedule of operations (*Cédula de Operación Anual* or COA), are included in the database. The rest of the industrial establishments are either micro-enterprises or commercial operations. However, the lack of a clear definition of industrial establishments included in the database adds to uncertainty in estimating emissions from the industrial sources of air pollution in the MCMA. Further, the large and medium industries are reported to comply with the current emission norms, while smaller and micro establishments are understood to be large polluters (Molina and Molina 2002). This means that the emissions reported in the emissions inventory are systematically underreported.

Of the total 6,280 industries included in the MCMA database for 1998, about 59% of these industrial establishments are located in the DF part of the metropolitan area, and the other 41% are located in the State of Mexico. Of the total industries in

[2] CAM has used the restricted definition of the MCMA; it includes only 16 municipios from the State of Mexico, as opposed to 37 municipios included in the analysis by the author of this study. This could be one of the reasons for discrepancies in the number of establishments.

Figure 3.9 Distribution of the Industrial Establishments in the MCMA (1998)



Source: INEGI 1999

the MCMA, 44% fall under the federal jurisdiction and 56% under the local jurisdiction.

3.4.2 Two-pronged Regulatory Authority and Jurisdiction

The industrial sector is divided into two jurisdictions, federal, and local. Article 111 of the general law of ecology and environmental protection (*Ley general de equilibrio ecológico y la protección al ambiente* or LGEEPA), in which the activities for each jurisdiction are classified, puts chemical, petroleum and petrochemical, paints and inks, metallurgy, automotive, cellulose and paper, cement, asbestos and glass, power generation, and water treatment in the federal category. All the other industries that are not listed above are considered local. Each of the registered industries is regulated by the respective jurisdiction, i.e., federal or local, on the basis of the above-mentioned classification. In the case of the MCMA, some industries that conform to

Table 3.6 The Reported Distribution of Industries in the MCMA (1998)

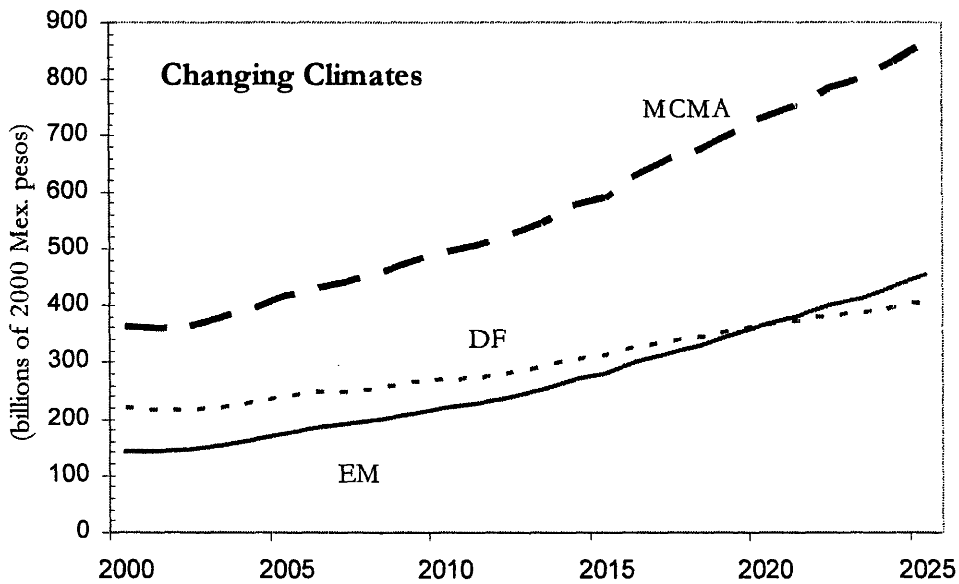
	Jurisdiction				**Total**	
	Federal		Local			
Location	Number	%	Number	%	Number	%
Federal District	1933	30.8	1792	28.5	3725	59.3
State of Mexico	856	13.6	1699	27.1	2555	40.7
Total	2789	44.4	3491	55.6	**6280**	100.0

Source: CAM (2001)

the above-mentioned categorization fall under the federal jurisdiction, irrespective of their physical location in the State of Mexico or in the DF, while other industries fall under local jurisdiction. The federal Ministry of Environment or SEMARNAT determines environmental regulations for the industries under the federal jurisdiction. The local industries are governed by the laws and regulations issued by local environmental authorities. The distribution of industrial establishments located in the DF and the EM, under federal or local jurisdiction, is tabulated in Table 3.6. The majority of industries in the DF fall under federal jurisdiction, whereas majority of industries in the EM fall under local jurisdiction.

In 1998, the State of Mexico contributed about 45% to the total manufacturing output of the MCMA and the rest came from industries in the DF. However, a reversal of the role is expected, as the rate of growth of the manufacturing sector in the EM is faster than that in the DF. Estimated output of the manufacturing sector of the metropolitan area of the DF and EM for Changing Climates scenario is plotted in the Figure 3.10.

Figure 3.10 The Manufacturing Sector Output from DF, EM and the MCMA in Changing Climates (2000-2025)



In the year 2022, the manufacturing output in the EM equals that of the DF, and then continues to increase. This is a likely result of setting up of new manufacturing facilities and higher rate of industrial sector growth in the EM than in the DF.

3.4.3 The Industrial Sector in the MCMA

From the perspective of the number of industrial establishments, the chemical industry dominates the industrial landscape, followed closely by the metallic products industry. The categorization of the industries is based on the Mexican national system of industrial classification. The distribution of various industries located in the MCMA is given in Table 3.7.

Table 3.7 The Sub-sectoral Distribution of the Reported Industrial Sources of Emissions in the MCMA (1998)

Industry Name	Number	%
Chemical Industry	1133	18.8
Metallic Products	934	15.5
Medium Term Life Products	626	10.4
Printing Products	553	9.2
Textile Industry	535	8.9
Food Industry	486	8.1
Different Consumption Products	428	7.1
Long Term Products	379	6.3
Non-Metallic Mining	325	5.4
Woods and Byproducts	274	4.6
Metallic Mining Products	237	3.9
Vegetal and Animal Products	63	1.0
Others	23	0.4
Petrochemical	17	0.3
Power Plants	5	0.1

Source: CAM (2001)

The emission profile of an industry is not necessarily proportional to the number of industries in that sector, but related to the nature of activity, fuel consumed, and size of the establishment. Annual emissions of industry categories in the MCMA for 1998 and 2000 are reported in Table 3.9 and 3.10 respectively.

3.4.4 Energy Consumption by the Industrial Sector

The industrial sector in the MCMA is a major consumer of fuels and electricity. Of the total 579PJ of the final energy consumed in the MCMA in 1998, about half of it was consumed by the industrial sector (Bazan, 2000). Energy consumption patterns play an important role in determining the emission profile, as combustion of fuels is a dominant source of criteria pollutants. The total fuel consumption in the MCMA is listed in Table 3.8

The industry uses 18% of the total fuels consumed in the MCMA, while electric power generation consumes about 10%. Further, about 78% of the fuel consumed by industry is gaseous (either natural gas or LPG) which are generally cleaner than diesel or fuel-oil. To model penetration of the gaseous fuels, natural gas and liquid petroleum gas, we define a parameter clean fuel fraction (CFF), the ratio of energy consumed in gaseous form to total energy consumed.

Table 3.8 Total Non-electric Energy Consumption in the MCMA (1998)

Sector / Fuel Type	Power Generation	Industry	Trans-Portation	Comm/Govt & Resid.	Agriculture	Total by Fuel	% by Fuel
Gasoline			213.9			213.9	37
Natural Gas	56.5	76.4		3		136	24
LPG		5.1	12	97.9	0.3	115.2	20
Diesel			48.9			48.9	9
Industrial Fuel		23.1				23.1	4
Solid Fuels				19.4		19.4	3
Other Intermediates			13.6		0.7	14.3	3
Sector/Grand Totals	56.5	104.6	288.3	120.3	1	**570.7**	100
	(PJ)	(PJ)	(PJ)	(PJ)	(PJ)	(PJ)	%
Sector %	10	18	51	21	0	100	
	%	%	%	%	%	%	

PJ = Peta (10^{15}) Joule
Source: Bazan (2000)

Diesel, natural gas and fuel-oil have traditionally been the main fuels used by the industrial sector in the MCMA. Estimates of the total industrial fuels consumed in the MCMA indicate that about 4% of the final energy consumed comes from diesel and fuel-oil (Bazan, 2000). Fuel-oil is one of the main sources of SO_2 in the air due to its higher sulfur content. Over the last few years, the MCMA industries have been switching to cleaner fuels. The power plants that were using fuel-oil with 4% sulfur content switched to natural gas, while medium and small industry switched to fuel-oil with sulfur content 3%. The quality of diesel supplied in the MCMA changed from 2% to 1% sulfur content in 1986 in response to increasing environmental concerns. Fuel quality saw further improvements when PEMEX started supplying 0.5% diesel and industry using 3% sulfur fuel-oil switched to 1% sulfur fuel-oil, or to natural gas. For the last six years, PEMEX is reported to have been providing low-sulfur fuel-oil (1% sulfur), which is anticipated to be phased out by switching to low-sulfur diesel (Favela, 2000). Implications of this decision are massive capital investments in production, supply, and distribution networks for low-sulfur fuels. This switch over is likely to result in benefits in terms of the improved air quality in the MCMA.

The electricity consumption by the industrial sector has been on the rise. Since only 20% of the electricity demand of the MCMA is met by the local generation. And the rest is imported from outside the MCMA, only a portion of it contributes to local air pollution. Yet all of the consumption of electricity contributes to greenhouse gas emissions. The industry is estimated to be using more than half of the total electric power supply in the MCMA. The growth rate in the electricity demand by industry has surpassed the overall demand for electricity in the MCMA. The share of electricity consumption in the MCMA by the industrial sector dropped with the decline in economic activity in 1995, but it quickly regained its share when the economy recovered. In 1998, 55% of the total electricity consumed in the MCMA was being used by the industrial sector.

3.5 Emissions from the Industrial Sources

The 1998 emissions inventory for the MCMA reported the point-source emissions in 14 categories, including power generation. The emissions from the 13 categories are shown in Table 3.9. The emission categories used in the 2000 emissions inventory are different from that of 1998. The 2000 emissions inventory (CAM 2004) uses INEGI's *Clasificación Mexicana de Actividades Y Productos 1999* (CMAP) for reporting emissions from the manufacturing sector. Table 3.10 lists emissions from the MCMA industrial categories for the year 2000.

According to the 1998 emissions inventory, the chemical industry is the largest emitter of SOx, CO, and hydrocarbons among all the industry categories, whereas the food processing and non-metallic minerals are largest emitters of PM. The non-metallic minerals and metallic product industries are the dominant emitters of NO_x. Although CO emissions from industry are negligible as compared to the transportation sector, the chemical industry is a leading CO emitter, representing about 30% of the total industrial CO emissions (Table 3.9).

The basic metal industry is the largest PM_{10} emitting industry in the MCMA manufacturing sector, contributing about one-fifth of total manufacturing PM_{10} emissions (see Table 3.10). The chemical industry is the leading emitter of sulfur dioxide; it emits 23% of the total manufacturing SO_2 emissions, closely followed by the textile industry (22%). The non-metallic minerals and the chemical sector are the two largest emitters of NO_x; they contributed 33% and 17% to the total manufacturing NO_x emissions in the year 2000. The chemical (34%) and the paper and printing products (26%) lead the pack of hydrocarbon emitters. Since the CO emissions from stationary sources are very small, they are not included in the Table 3.10.

Table 3.9 Annual Emissions from Industry Categories and Their Share (1998)

Industry Category	PM10		SO2		NO_x		HC	
	Tonne	%	Tonne	%	Tonne	%	Tonne	%
Food processing	515	17.4	1103	8.9	924	5.3	416	1.7
Non-metallic minerals	504	17.1	1698	13.7	4570	26.2	765	3.2
Chemical	415	14.0	2299	18.5	1335	7.7	6305	26.3
Textile (clothing)	379	12.8	2262	18.2	1316	7.5	386	1.6
Metallic minerals	249	8.4	714	5.7	513	2.9	291	1.2
Wood and derivatives	216	7.3	2295	18.5	1066	6.1	1002	4.2
Metallic products	175	5.9	774	6.2	4432	25.4	3024	12.6
Durable Goods	140	4.7	302	2.4	2128	12.2	2654	11.1
Medium Life Goods	120	4.1	86	0.7	624	3.6	1457	6.1
Products for consumption	73	2.5	261	2.1	129	0.7	873	3.6
Others	62	2.1	172	1.4	157	0.9	3024	12.6
Vegetable and Animal Products	61	2.1	287	2.3	109	0.6	12	0.1
Printing products	46	1.6	173	1.4	145	0.8	3723	15.6
Total	**2,955**	**100**	**12,426**	**100**	**17,448**	**100**	**23,932**	**100**

Source: CAM (2001)

3.5.1 Analysis of the MCMA Industrial Emissions Inventory

In 1998 (Table 3.9) emissions inventory, the classification used for the industries in the MCMA emissions inventory was different than that in the 2000 emissions inventory. Therefore sub-sector level comparisons and analysis of the emissions inventory may not be appropriate. In this section, I analyze the industrial emissions in the MCMA for 1998 and 2000, and identify the largest contributors for different pollutants.

In 1998, food processing sector was the largest emitter of PM_{10}, followed by the non-metallic minerals sector (e.g., cement manufacturing). The chemical, and wood and wood products sub-sectors were largest contributor of SOx emissions (18.5% each). And for NO_x emissions, largest emissions came from the non-metallic minerals and metallic products sector. Chemical sub-sector was the biggest contributor to the industrial hydrocarbon emissions in the MCMA.

Table 3.10 The MCMA Manufacturing Sector Emissions (2000)

ISIC /CMAP	Sector	PM_{10} (t/y)	SO_2 (t/y)	NO_x (t/y)	HC (t/y)
31	Food products, Beverages and Tobacco	366	1109	1130	1384
32	Clothing, Textiles and Leather Products	350	2213	1307	611
33	Wood and Wood products	130	240	70	901
34	Paper, Paper Products, Printing, etc.	163	1793	1194	5742
35	Chemicals, Petroleum, Coal, Rubber, etc.	394	2332	2311	7453
36	Non-Metallic Minerals	256	768	4350	191
37	Basic Metal Industries	513	615	1122	516
38	Metallic Products, Machinery and Equipment	374	973	1441	4643
39	Other The manufacturing Industries	61	229	166	423
	Total	**2,607**	**10,272**	**13,091**	**21,864**

ISIC = International Standard Industrial Classification
t/y = Tonne/Year
CMAP = *Clasificación Mexicana de Actividades Y Productos*
PM_{10} = Particles smaller than 10 micrometer in diameter
SO_2 = Sulfur dioxide
NO_x = Oxides of Nitrogen, generally represented as NO_2
HC = Hydrocarbons
Source: Emissions Inventory for the MCMA for 2000 (SMA 2004)

In 2000, the emissions inventory used a different classification (see Chapter 6 for details). Basic metal industries contribute 20% of the total industrial PM_{10} in the MCMA, followed by chemical sub-sector with a 15% contribution. The chemical sub-sector (23%) is largest contributor to SOx emissions followed by textile sub-sector (22%). The non-metallic minerals (33%) sub-sector emits largest amount of NO_x, followed by chemical sub-sector (18%). The chemical sub-sector remains largest contributor to the industrial hydrocarbon emissions in 2000.

All industrial air-emissions show a declining trend from 1998 to 2000. The MCMA industrial emissions for all pollutants in 2000 declined between 9 to 25%, from there 1998 levels (Table 3.9; Table 3.10). PM_{10} emissions registered a 12% decline, SO_2 emissions reduced by 17%, NO_x emissions reduced by a quarter, and hydrocarbon emissions declined by 9%. It is not clear if the cause of the decline in industrial emissions was change in the level of industrial output, resulting from recession in the demand from the US, or it was due to changes in the emissions accounting methods.

3.6 Industrial-Environmental Policymaking in the MCMA

The industrial-environmental policymaking in the MCMA can be best understood by looking at the development of environmental policymaking in Mexico. The industrial-environmental policy in Mexico is a recent phenomenon. Before 1970 there were practically no criteria for management of industrial pollution (INE-SEMARNAP 2000). In 1971, the introduction of the Federal Law for the Prevention and Control of Pollution (*Ley Federal para Prevenir y Controlar la Contaminación*) provided a legal basis for policy and regulations for environmental pollution controls from the industrial sources. In subsequent years, the environmental protection laws were further strengthened. Another important piece of legislation was passed in 1988, known as General Law for Ecological Equilibrium and Environmental Protection (*Ley General de Equilibrio Ecologico y Proteccion al Ambiente* or LGEEPA). On basis of the experience gathered in the eight years, this LGEEPA was further modified in 1996 to include some more aspects of regulation such as decentralization, execution and vigilance, incorporation of economic instruments, etc. The Environmental Regulation of Industries (*la Regulacion Ambiental de la Industrial*) and LGEEPA together provide a legal framework for environmental policymaking in Mexico. However, the environmental policies have mostly been geared towards a command-and-control approach, which relies on setting up of environmental standards, and ensuring their compliance. Several official norms lay out the standards for emissions from various sources, and are listed in various documents. For example, the NOM-039-ECOL-1993, published in 1993, lays out emission norms from plants producing sulfuric acids. There are several institutions that play a key role in the environmental policymaking in the MCMA.

3.6.1 The Institutional Framework

Several federal and local institutions are responsible for environmental policy making and its effective implementation in Mexico. In the context of the industrial sources of air pollution in the MCMA, there are three jurisdictions, one Federal, and two local (Federal District and the State of Mexico).

SEMARNAT: The Mexican Ministry of Environment (*Secretaria de Medio Ambiente y Recursos Naturales* or SEMARNAT) is the chief federal institution responsible for identifying pollution prevention goals and setting up monitoring and regulatory framework under the existing regulation, such as LGEEPA.

INE: *Instituto Nacional Ecología* or INE provides crucial support to SEMARNAT by conducting research and analysis in the area of environmental protection.

PROFEPA: *Procuraduría Federal de Protección al Ambiente* or PROFEPA, plays a key role in ensuring success of any environmental regulations by taking up the role of environmental compliance and auditing. PROFEPA is also responsible for ensuring that the environmental standards set in various official norms or standards (*Norma Oficina*) are complied. It has authority to levy fines or fees on entities not complying with the law.

At the local level, in DF, Secretaria de Medio Ambiante and in EM, Secretaria de Ecología are the primary institutions responsible for formulation and compliance of environmental policy making. In reference to environmental pollution in the MCMA, a metropolitan Environmental Commission (CAM) was set-up to collaborate and initiate coordinated policy making efforts. INE-SEMARNAP (2000) provides a detailed description of the institutional framework for environmental policymaking in Mexico.

In this chapter, I outlined the definition of the MCMA as used in this research. Further, I analyzed emissions in the MCMA and portrayed the role of industries in the emissions inventory. Finally, I compared the industrial emissions inventories for 1998 and 2000, and note a sharp decline in industrial emissions in this period. I also outline the policymaking framework for the MCMA, in the context of industrial sources of air pollution. In the next chapter, I outline the three scenarios developed for the MCMA, called "Growth Unbound", "Changing Climates", and "Divided City." The three scenarios are called Future Stories, and lay out the ground work for developing energy demand and emissions scenarios from the MCMA for period 2000-2025.

Chapter 4

Managing Uncertainty: Scenario Analysis and the Future Stories

Scenario planning and analysis has long been used as a tool for dealing with uncertainty in strategic planning (see Wack 1985; Wack 1985a; Schwartz 1996). The task of estimating impacts of numerous options on a range of variables of interest is a difficult one. Complex interactions among the variables, the non-linear nature of relationships, and numerous feed-backs make it difficult to model and predict the behavior of the variables of interest. Various tools, such as systems dynamics, have emerged in response to the challenge of dealing with large-scale complex systems (Sterman 2001). One famous application of this methodology to model the world's resources is found in "The Limits to Growth" (Meadows et al. 1972). However, applications of such tools to some of the more challenging problems pose many difficulties due to the lack of necessary data. Often, a lack of detailed data and understanding of the causal mechanisms and their quantification prevents us from modeling such complex systems. It is in this context, that scenario analysis or scenario planning proves to be a useful tool for capturing uncertainty and its impact on the outcomes of interest, and helps us in preparing for an uncertain future. For the purpose of integrated assessment of air pollution in the Mexico megacity, Dodder et al. (2004) developed three macroeconomic and socio-political scenarios, called Future Stories. The Future Stories are internally consistent, plausible sets of macroeconomic and socio-political drivers, which represent different evolutionary paths for the MCMA. Future Stories are developed to understand the dynamic nature of various internal and external factors, and their impact on the various activities (grouped into several sectors, such as the industrial, commercial and services, informal production, residential, transportation and power sectors) that generate air pollution. The three Future Stories are called as Growth Unbound (GU), Changing Climates (CC), and Divided City (DC). The main features of each of the three Future

Stories are given in Table 4.1. The drivers of each Future Story are identified in Table 4.2. In this chapter, I will describe the three Future Stories, and show how they relate to the demand for goods and services in the manufacturing sector (Dodder and Vijay et al. 2004), and finally outline how they will influence the level of industrial output, fuel-mix, and emission controls by the manufacturing sector in the Mexico City Metropolitan Area (MCMA).

These scenarios have been referred to as Future Stories, as they are not predictions of the future. Rather, they are descriptions of possible long-term pathways the metropolitan area could follow. Since the three Future Stories represent as wide range of scenarios, it should be possible to prepare and identify well performing and robust strategies by comparing performance across these scenarios. By doing this policymakers can identify what to avoid, while responding to the dynamic nature of megacities' growth over time.

4.1 Global, Regional and Local Scenarios

There is a vast body of literature that describes global, regional, and local scenarios. The Intergovernmental Panel on Climate Change (IPCC)'s special report on scenarios (IPCC 2000) deals with the global macroeconomic drivers and their impacts on energy usage and greenhouse gas emissions. The Shell scenarios deal with the global forces and their potential impacts on strategic response by the businesses (Davis 2002). Martinez (1990) has developed scenarios for the Mexican energy planning. Manzini (1999a) uses these scenarios for evaluating energy technologies towards a sustainable Mexico. Dodder et al. (2004) has developed the most comprehensive scenarios for exploring a range of futures for the MCMA that are relevant to development of air-pollution control strategies.

Most of the scenarios deal with the macro variables at the national level, focusing on specific drivers such as demographic, economic, political or technological trends. Generally, these scenarios lack a decision-making component. The scenarios developed by Dodder et al. (2004) for the Mexico City Metropolitan Area are different. These scenarios are not only targeted to support decision-making regarding air quality management, but also enable modelers to use several quantitative variables to estimate emission trends for a particular sector (for example, see Roth 2003; Aoki 2002). The three future stories include a broad range of macro-drivers – economics, society, urban form, technology, politics, and the environment – all of which are important factors in emissions trends and air quality management.

The MCMA is a heterogeneous region, as it consists of two neighboring political entities, the Federal District (*Distrito Federal* or DF) and the State of Mexico (*Estado de Mexico* or EM). Although the two regions are integrated socio-economically, some parts of the MCMA are very different from the others. Moreover, the political and jurisdictional differences in different parts of the MCMA, and different levels of industrialization and economic growth makes it more difficult to come up with internally consistent set of coherent stories for the whole region.

In general, the scenarios for Mexico presented by various modelers vary in their level of quantification. Some scenarios can be only descriptive, whereas others can be highly quantitative. Highly qualitative scenarios, such as those of Mazarr (1998), and the quantitative scenarios, such as the econometric modeling in some chapters of Millán and Concheiro (2000), are some representative examples of these two extremes. Although the basis for the logic of the future stories is qualitative, the three future stories presented in this chapter have been extensively quantified in the form of representative indicators so that the air quality impacts of the scenarios can be modeled by various researchers. However, the quantification does not include, for example, econometric modeling to project future growth rates. Instead, the quantification results from the dialogue and expert judgment of an interdisciplinary group of primarily Mexican analysts and stakeholders who participated in the initial

Table 4.1 Characteristic of the Future Stories

DRIVING FORCES	FUTURE STORIES		
	Growth Unbound	Changing Climates	A Divided City
Economics	5% growth Finance and services-led Sustained high levels of investment (I/Y)	4% growth Balanced sectoral growth	3% national growth Heavy on manufacturing
Society	Security remains problematic Civic participation low Income inequalities persist	Shrinking income inequality Convergence between EM and DF Growing civic participation	Income inequality worsened Large informal sector Urban instability Civic participation vocal
Urban Form	Sprawl & auto dependence Expulsion & densification "Santa Fe" type development in the EM Moderate population growth	Consolidation & densification Shrinking household & family size Lower population growth	Expulsion & expansion High population growth Large portion of irregular households
Technology	Rapid turnover of technologies, but… Lagging behind US standards on efficiency standards and emissions control equipment	Convergence with US technologies High investment in S&T Rapid learning curve and diffusion of "best practices"	Long lag time with US technologies Sensitivity of equity issues
Politics	Government intervention low Institutional reforms slow	Government intervention high in investment and enforcement Better accountability Metro governance successful	Fragmentation of parties Dynamic and unstable Inter-jurisdictional conflict Corruption high
Environment	Environmental issues not addressed Public apathy and resignation	Heat island impacts shift local environmental attitudes International actions (Kyoto) and bottom-up with local NGOs	Social problems overshadow environmental issues Water become the critical environmental issue

Source: Dodder et al. 2004

scenario development exercise, and supported the refining of the quantitative indicators after the qualitative narratives were developed. The indicators also drew on projections for "business as usual" scenarios, such as population scenarios developed by the Mexican National Population Commission (Comisión Nacional de Población or CONAPO) in Mexico – modifying those scenarios to represent more unanticipated scenarios – whether optimistic or pessimistic – and statements of policy goals such as levels of investment in science and technology and research and development. Reasonable values for variables such as economic growth rates, population trends, and urban expansion, were chosen such that it would best reflect the dynamics of the MCMA under highly contrasting circumstances.

4.2 The Three Future Stories

In order to develop the three Future Stories for the MCMA, Dodder et al. (2004) first identified key focal issues, namely, public health, economic growth, social welfare and ecological health. Next she related these issues to key local factors such as demographics, employment, and linked those macro drivers, of a more global character, with how they would influence local factors. Macro drivers are the variables that are not under influence or control of policymakers, and Dodder et al. have used them as given as exogenous local and global political, economic, and social forces. Each of the Future Stories is driven by a pair of specific macro drivers. In total, there are six macro drivers: economics, society (particularly inequality across the sections of society), environment, politics, technology and urban form. The future stories and their key macro drivers are shown in Table 4.2.

Table 4.2 Future Stories and the Key Macro-drivers

Future Story	**Growth Unbound**	**Divided City**	**Changing Climates**
Macro Drivers	*Economic Growth* (Economic growth is good but inequality increases, environmental awareness is low, demand for goods increases)	*Society* (Inequality, social and political conflicts take the center stage, hindering economic growth)	*Technology* (Penetration of end-of-pipe and process controls is high, capital stock is renewed at high rate)
	Urban Form (Higher income levels lead to urban growth and sprawl, leading to increased growth in informal sector)	*Politics* (The neighbouring political entities have different agenda, institutions lack political will to implement policies)	*Environment* (Higher level of consciousness about environmental impacts of development, leading to political action)

Source: Dodder et al. (2004)

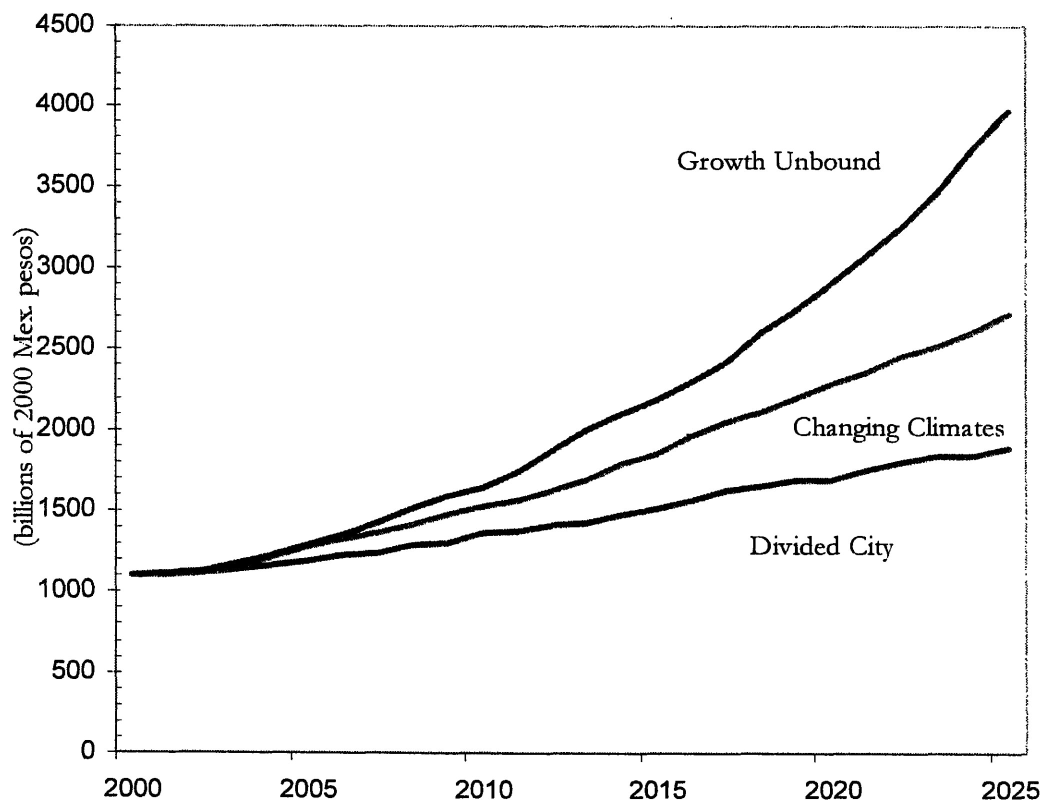
4.2.1 Growth Unbound

The Future Story called Growth Unbound (GU) is primarily driven by strong growth in the national economy, and low population growth. Urban form is another important driver in this scenario. Urban sprawl is a dominant outcome of the economic growth, leading to more population living in suburban areas, and relying on the private automobile to meet their mobility needs. The gross domestic product (GDP) of the national economy is assumed to grow at an average rate of 4.5%-5% per annum.

The manufacturing and financial services are assumed to do well, whereas commercial and service sectors experience slower growth in this scenario. Due to high rates of growth, the demand for goods and services is also high, leading to higher levels of production, and/or higher levels of imports from outside the region. On one hand, the increased level of production by the manufacturing sector is likely to result in higher energy consumption and higher air emissions from the industrial sector in the MCMA. On the other hand, if the demand is primarily met by increased imports, air pollution from the transportation sector will rise as additional freight movements occur. Increased demand of goods by the end-users will increase the demand for the intermediate goods affecting industrial output in the MCMA.

Further, this scenario envisages smaller household sizes, combined with a low-density suburban development, leading to a higher number of households as compared to other scenarios. The demand for certain durable goods, such as refrigerators, is directly dependent on the number of households, and not on population alone (Roth 2002). The demand for these goods in this scenario will also rise.

Figure 4.1 Manufacturing Economic Output for the Three MCMA Future Stories



Source: Dodder et al. (2004)

4.2.2 Changing Climates

Changing Climates is characterized by rapid adoption of advanced and cleaner technology by various economic sectors in the MCMA. The global recognition of the threat of climate changes caused by accumulation of greenhouse gases is recognized, and the heat island effect also plays a key role in shaping policies in the MCMA. The growth rate of GDP at the national level averages 3.5% in this scenario. Commercial and financial services grow at a higher rate and there is a shift away from a manufacturing- to service-based economy in the region. Income inequality and imbalance in the regional growth is closing, and civic participation is increasing. Population growth is modest, and the urban-sprawl is held in check. Household sizes shrink. In the arena of technology, integration and adoption of the best practices takes place at a rapid rate. Energy-intensity reduction in all the sectors is pursued aggressively, and is able to achieve a rate of decline to the tune of 3% per annum. Structure of the MCMA manufacturing sector is shifting from high energy-intensity production to low energy-intensity activities. Energy demand by the industry is changing its characteristics, due to modernization of industrial processes. The share of electricity to the total energy demand in the manufacturing sector is on rise. The institutional integration across political lines is more commonplace, and policies are governed by common interests and greater stakeholder participation.

4.2.3 Divided City

The scenario Divided City assumes a low growth rate of the national GDP. The share of non-financial services and informal sector in the economy is expected to grow. The manufacturing sector witnesses only a modest growth in output. The primary drivers of this scenario are the socio-political dynamics of the region. The social fabric of the MCMA is stressed, as the income inequality among the population increases. There is a growth in the activities of the informal sector, which provides employment to the majority of the population, and produces a significant share of output of the MCMA region. Overall this scenario represents a fractured society, marred by low economic growth in the formal sector, leading to a spread in the urban area, with high number of irregular settlements. Inter-jurisdictional conflicts increase, leading to reduced attention on solving common problems facing the region, including the ability to implement coordinated air-quality improvement measures. Social problems take priority, and environmental issues take a back-seat. Technology transfer, and the capital stock turn-over by the industry sector is slow, leading to a reduced rate of decline in energy intensity, and low penetration rates of end-of-pipe emission controls by the industry. Demand for goods and services are high, due to high population increase, but primarily it is met by the informal sector.

4.3 Demand for Goods and Services[1]

The Future Stories, as described in Section 4.2, drive the demand for goods and services through economic growth, changes in the sectoral composition of the economy, population growth, average household size in the MCMA, and other variables that define the Future Stories. To understand how these variables affect the demand for goods and services, and ultimately, the emissions that result from the production of these goods, and consumption and transport of those goods and services, one has to look not only at the individual sectors – residential, informal and commercial, industry, and freight – but also at the interactions between these sectors. The schematic in Figure 4.2 represents the linkage between various factors affecting the demand for goods and services.

The primary driver for demand in the MCMA is the household sector. The household sector demand consists of durable goods, non-durable goods, and services, such as transport, energy, water etc. Various parameters affect, and are affected by

[1] The material presented in this section was developed with members of the Mexico City project scenario analysis team, for a book chapter, Demand for Goods and Services. Andres F Montalvo, Kellyn Roth, Ali Mostashari, Chizuru Aoki, and Alejandro Bracamontes contributed to the development for their respective sectors. Rebecca Dodder and Samudra Vijay were responsible for integrating the information for all the sectors.

the demand for goods and services. These factors affecting demand for final and intermediate goods and services are often interrelated.

Demand for goods can be categorized as demand for final goods and demand for intermediate goods. Final goods are eventually consumed by the end-user. Final goods could be durable goods, such as refrigerators, televisions, automobiles, or they could be non-durable goods, such as food, paper etc. They could be tangible, like house appliances, and intangible, like most services.

Intermediate goods are those used by the industry to produce final goods. Change in the demand for final goods could be used to infer primary and secondary demand for intermediate goods and services, by using technical coefficients of production within an input-output framework for a given economy (Miller and Blair 1985; Avrom 1991). However, due to the unavailability of such a framework for the Mexico City Metropolitan Area, it is hard to establish exact quantitative relationship between final demand, and the demand for intermediate goods. Below, I will outline the parameters that affect demand for goods and services for various sectors, and then use a sectoral approach to delineate the role and dynamics of these parameters in determining demand for goods and services by a particular sector.

Whenever possible, we used macroeconomic indicators to estimate demand for the final goods and services, however, lack of availability of relevant data limits our ability to do so extensively. We have also used a bottom-up approach to estimate the demand for goods and services.

Below I summarize the trends in each of those drivers, which will impact the demand for goods and services in the MCMA. Divided City represents the most pessimistic scenario from the viewpoint of economic performance, as well as income inequality. Aggregate production grows slowly, as do incomes, with the informal sector continuing to be a major share of economic activity. GDP per capita, measured in constant 2000 pesos, rises only slightly, since the little economic growth there is, continues to be overwhelmed by persistently high population growth. Urban sprawl, primarily driven by irregular settlements, is high, particularly in the State of Mexico, straining the existing infrastructure, and pushing the demand for new infrastructure for electricity, gas, water and sewage.

In Changing Climates, with a national average annual GDP growth of 3.5%, Mexico City does not see the sustained, high growth rates of the Growth Unbound Future Story, however, the income inequality of the MCMA shows signs of improvement, with more equitable growth between the EM and the DF. Income levels rise, due in part to slower population growth, and urban growth is better managed, with re-densification of the city center, and a consolidation of growth and densification of the more newly urbanized areas in the MCMA periphery in the State of Mexico.

In Growth Unbound, the national average annual GDP growth rate is high, resulting in higher levels of income for the residents of EM and DF. Urban sprawl results in changes in the land-use pattern. Higher income levels translate into higher demand for consumer and durable goods, resulting in increased production from the manufacturing sector, and thus leading to increased local air pollution. Imports from other regions also increase leading to increased emissions from the freight transportation sector.

Using the three Future Stories, we explored the consequences of possible shifts in the economic structure of the MCMA. It should be emphasized that the structural composition of the national and MCMA level economy are not forecasts, nor have they been modeled econometrically. Instead, given the 25-year time horizon, and the

Table 4.3 Changing Economic Structure (rise/fall in % share of GDP)

	Divided City			Changing Climates			Growth Unbound		
	Nat'l	DF	EM	Nat'l	DF	EM	Nat'l	DF	EM
Agriculture, Cattle, Fishery	–	=	–	–	=	–	–	=	–
Mining, Extraction Activities	–	=	–	–	=	–	–	=	–
Manufacturing Industry	–	–	+	+	–	–	+	+	+
Construction	+	+	–	–	+	–	+	+	+
Electricity, Gas & Water	+	+	+	+	+	+	+	+	+
Comm., Restaurants, & Hotels	+	–	–	+	+	+	–	–	–
Transport and Commerce	+	–	+	+	+	+	+	+	+
Financial Services	–	–	–	+	+	+	+	+	+
Other Services	+	+	+	–	–	–	–	–	–

Source: Dodder et al. (2004)
Note: A "+" sign indicates increase in the share, a "–" sign indicates decrease in the share; "=" indicates no change in share.

uncertainties inherent in modeling over this time period, we chose three possible directions for the economic structure – the relative shares of manufacturing, services, agriculture, construction in total GDP – to evolve in ways that would be consistent with the narratives and the other driving forces of the Future Stories. The purpose is was not to forecast these variables, but rather to examine the implications, in terms of air quality, of the different possible futures for the MCMA. That said, the table below highlights the changes in the economic structure and the national level, and for the DF and the urbanized areas of the State of Mexico.

In all of the Future Stories, the share of agriculture, livestock, fishery, and mining and other extraction activities, remains constant or falls. These sectors are already negligible in their contribution to economic output in the MCMA, typically with less than 1% of total output, and most signs indicate that their share of output will continue to be diminished.

In Divided City, there is slow manufacturing growth at both the national and MCMA level. There is slightly more growth in manufacturing at the level of the MCMA (2.3% annual growth in the MCMA rather than 2.1% at the national level) as the MCMA continues to be the economic center of Mexico. Rather than seeing a shift to a more services and commercial-based economy (whether in the form of commercial, restaurants and hotels, for Changing Climates, or financial services, for Growth Unbound) which happens to a greater extent in the other two stories, Divided City remains more dependent on manufacturing, with high growth in electricity, gas and water to meet the demands of the rapidly growing population. In Growth Unbound, growth in manufacturing fuels the economy at the national level, with 5.1% growth. It is a bit slower at the level of the MCMA, with more services and financial services taking hold in the MCMA (more so in the DF than in the EM). The manufacturing growth in the MCMA continued to be concentrated more in the EM.

Table 4.4 Drivers of Demand for Goods and Services

	Future Story		
Future Story Variable	Divided City	Changing Climates	Growth Unbound
Population	High	Medium	Low
Households	Medium	High	High
MCMA GDP	Low	Medium	High
GDP per capita	Low	Medium	High
Income Inequality	High	Low	Medium
Economic Structure	See Table X		
Informal Sector Share	Large	Medium	Small
Urban Form	Irregular Sprawl	Contained Growth	Suburban Sprawl

Source: Dodder et al. (2004)

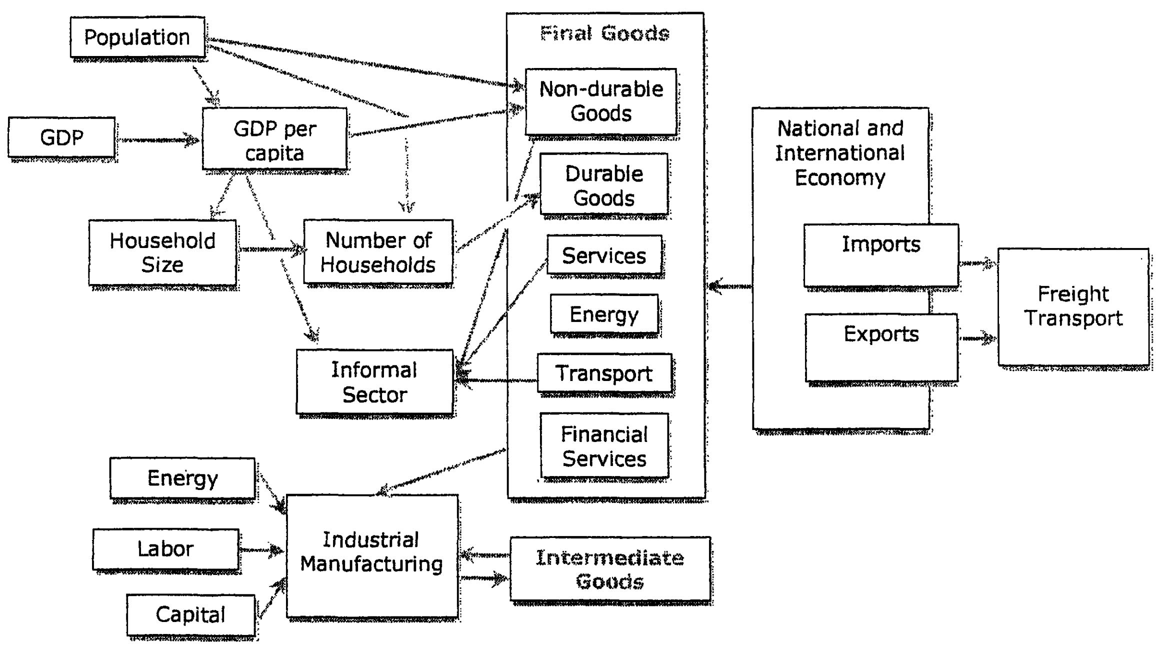
4.4 Implications for the Industry Sector

The macro drivers and other factors will affect response of the manufacturing sector in Mexico and in the MCMA. In this section, I discuss specific implications of the unfolding of each particular future story for the manufacturing sector.

4.4.1 Growth Unbound

In this scenario, economic growth is fueled by the growth in the manufacturing sector. National level growth rate of manufacturing industry averages at 5.1% whereas at the MCMA level, the growth rate is expected to be slightly lower, at 4.8%.

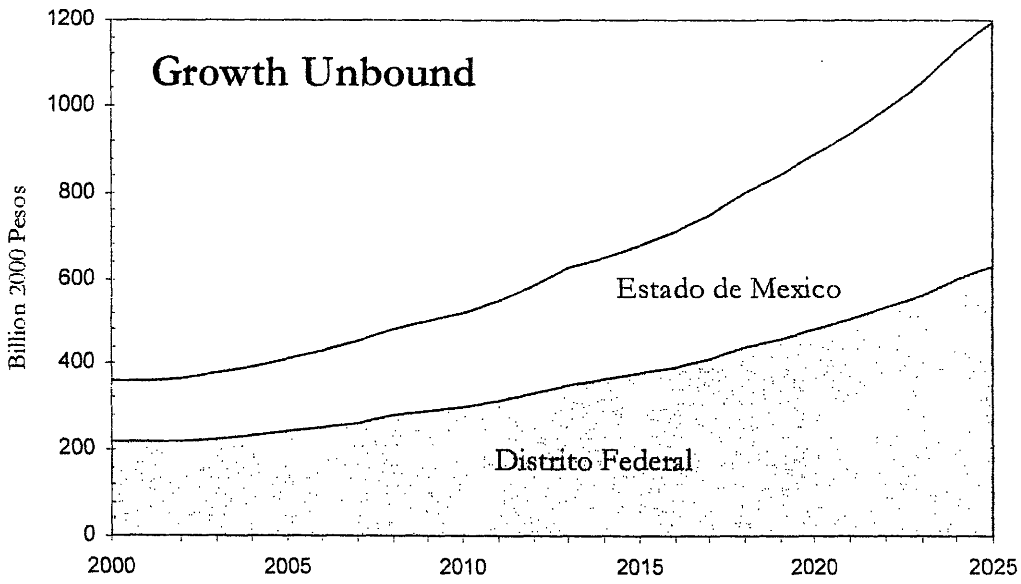
Figure 4.2 Factors Determining the Demand for Goods, Services and Freight



The difference in the national and local growth rates is due to the fact that the national level growth will be dominated and determined by the export-oriented *maquiladoras* outside of the MCMA. This scenario, if it unfolds, will strongly influence air-pollution levels in the MCMA. As I will show in the analysis, the growth in output dwarfs the impacts of energy-intensity reductions and structural shifts, in determining the level of air pollution. The manufacturing sector growth in this scenario will be concentrated in the EM, and not in the DF. The DF will play a key role by providing increased level of financial services for the sustained success of the manufacturing activity in the region.

The output from the manufacturing sector in the GU scenario from DF and EM is shown in Figure 4.3. Significant growth in output in DF and EM both will cause in crease in energy demand by the industry sector, leading to increase in air pollution.

Figure 4.3 Industrial Sector Output in DF and EM (2000-2025)



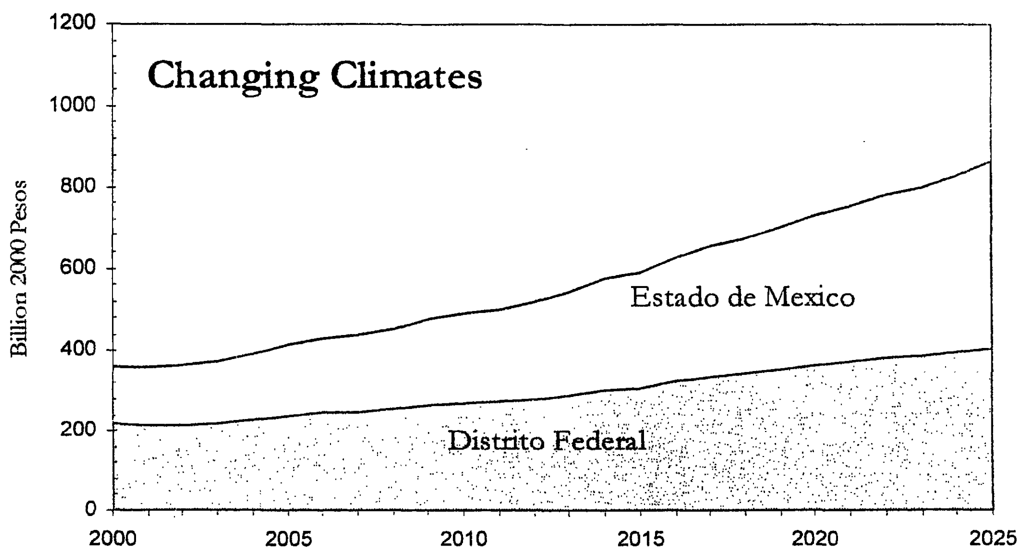
Source: Dodder et al. (2004)

4.4.2 Changing Climates

In this scenario, growth in the manufacturing sector output is 3.6% and 3.5% for Mexico and for the MCMA respectively. The primary drivers for this scenario are technology and the environment. On the one hand increased public consciousness about role of manufacturing sector in air pollution will force companies to be pro-active and be better corporate citizens. Moreover, access to investment to accelerate the stock turnover will result in changes in the manufacturing processes that will be more energy efficient. Shift in the product mix from more energy-intensive manufacturing to less energy-intensive manufacturing is also expected to happen in this scenario. Capital stock turnover and increased automation of industrial processes will rely more on the electrical energy than fuel-energy for many processes. This would shift the pattern of energy demand from fuels such as industrial diesel and natural gas to electricity, thereby reducing local air pollution. Also, this scenario is likely to see the most intensive adoption rate for the end-of-pipe emission control technologies by industry in the MCMA. Specifically, industries burning large amounts of natural gas should see more installations of low-NOx burners, or other combustion modifications. Manufacturing facilities, which still rely on liquid fuels, will see greater installations of particulate controls.

Output from the DF and EM manufacturing sector in this scenario is shown in Figure 4.4. The increase in the output is smaller than that in the GU scenario; however, in this case the output from EM surpasses output from the DF in 2022.

Figure 4.4 Industrial Sector Output in the DF and the EM (Future Story: Changing Climates)

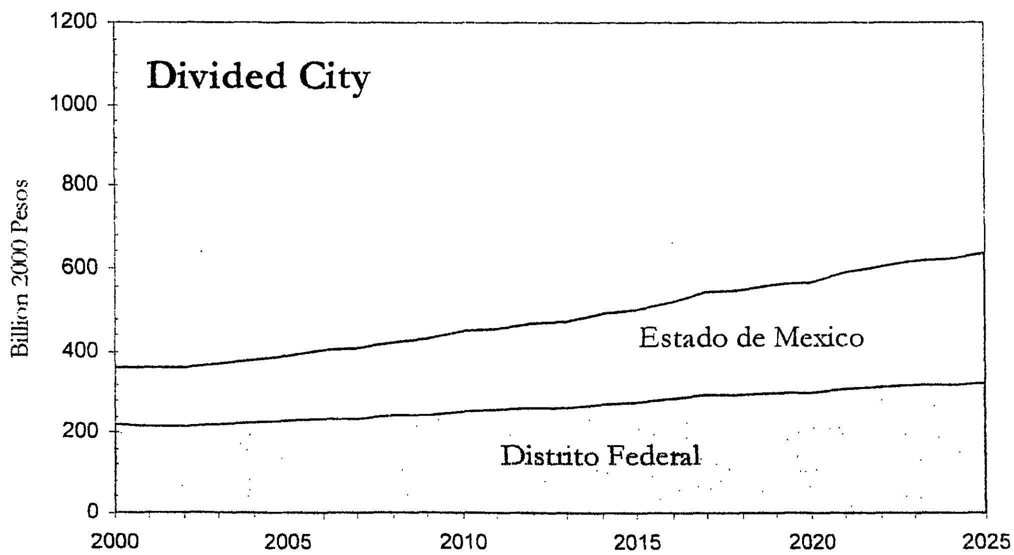


Source: Dodder et al. (2004)

4.4.3 Divided City

The rate of growth is expected to be slow in this scenario at the national as well as regional level. The rate of growth of output from the manufacturing sector at the national level is pegged at 2.1% per annum. The MCMA manufacturing sector growth rate for this scenario will be 2.3%, slightly higher than that in the nation, as MCMA continues to be the hub of the national economy and production activity. The growth rate in the rest of the nation is slower as the export-oriented manufacturing establishments or *maquiladoras* face stiff competition from the other manufacturing giants, such as China. Moreover, it is expected that the growth in the informal and commercial sectors will be more than that in the formal sector. Shift from a production economy to services economy is also slow. Low production growth will translate into low output by the industry, thereby lower fuel consumption and emissions. However, it is in this scenario that the investment in new technology and efficiency improvement are less likely to happen, thereby affecting the emissions. The output of the manufacturing sector in the MCMA, and Mexico under these scenarios is shown in Figure 4.5.

Figure 4.5 Industrial Sector Output in the DF and the EM (Future Story: Divided City)



Source: Dodder et al. (2004)

4.5 Summary and Conclusions

The MCMA scenarios or Future Stories presented in this section provide key exogenous variables to the energy demand and emissions estimation model developed in subsequent chapters. Some insights can be gained from the three Future Stories alone about energy demand and emissions implications in those scenarios. The growth rate in the GU scenario is highest; if this scenario is realized, the energy demand, and emissions from the industry will likely see a significant rise from current levels. It will be very difficult, if at all possible, to attain the ad hoc emissions reduction target from the industrial sources (50% from the current levels).

In the Changing Climate scenario, the energy and emissions will grow but the economic environment and increased environmental consciousness is likely to play a key role in determining industrial-emissions profile of the MCMA.

In the Divided City scenario, the growth of air pollutant emissions will be low, as compared to the other two scenarios, but for the wrong reasons. The emissions will be low, as the economic activity in this scenario will likely have less traction, resulting in reduced demand for goods and services, and thereby decline in energy demand and emissions.

The three Future Stories will be key guiding principles for deciding values of variables and parameters in the model to estimate emissions. For example, penetration rate of end-of-pipe controls in the scenario Changing Climates is likely to be higher than that in Divided City. I will use the qualitative descriptions of each of these scenarios to select values for the adoption and effectiveness of abatement options and policies.

In the next chapter, I will be presenting the framework for developing the model to estimated energy demand and emissions.

Chapter 5

Simulation Model and Parameters

In this chapter I present a simulation model developed to estimate emissions from the industrial sources in the Mexico City Metropolitan Area (MCMA). I also list the model parameters, and discuss the rationale for their choice. I incorporate the following parameters into the model: structural shift, fuel switching, energy intensity, technological change, adoption of end-of-pipe emission control technologies, and changes in the industrial activity initiated by the directed policies, as opposed to the change influenced by the macroeconomic environment. The simulation model is based on the IPAT (**I**nfluence = **P**opulation x **A**ffluence x **T**echnology) identity, discussed in detail in Section 5.1. Derivation of the model equation is inspired by the famous Kaya equation[1]. The Kaya equation also belongs to the IPAT family of models (IPCC 2000). The model uses a partial-equilibrium framework, i.e., any policy affecting the emissions creates no perturbations in other parts of the economy; the effects of the policy are assumed to be confined to the sector in question.

Section 5.1 describes the IPAT framework and outlines its origin and development. Section 5.2 develops the model for emission estimations and in Section 5.3, I critically review the model for its various shortcomings. Section 5.4 lists various parameters and a modification of the model to incorporate structural shift in the industry sector. Section 5 discusses the mechanisms of formation of and their emission factors, for the target pollutants.

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[1] The Kaya equation (see Kaya 1990; Ogawa 1991) is the most commonly used expression to discuss impacts of various components of human activity on the global climate change. The identity is expressed as: CO_2 = Population x (GDP/Population) x (Energy/GDP) x (CO_2/Energy).

5.1 The IPAT Family of Models

The simulation model captures impacts of various Future Stories or scenarios for the emission trajectories over a 25 year period. The model also helps identify the important components and policy levers that could aid in evaluating policy options to achieve the abatement targets in a cost-effective manner. The IPAT family of models uses a variation of the IPAT identity. The IPAT identity provides a simple but useful framework for the development of the simulation model. Its representation of the various drivers in a multiplicative form results in additive partial differences, which are easy to model, comprehend, and communicate. In this section, I discuss the IPAT identity and its variations.

5.1.1 The IPAT Identity

The IPAT identity is written as :

Impact (I) = Population (P) x Affluence (A) x Technology (T) **(5.1)**

The origin of the IPAT identity is credited to Elhrich, Holdren and Commoner, in early 1970s, and since then it has been used in its various forms to decompose and identify dominant elements of a particular trend affecting the environment (see Waggoner and Ausubel 2002; Chertow 2001; IPCC 2000). The original formulation of the equation served as a vehicle to investigate the impact of population and technology on the environment. The equation has largely been used to frame discussion around the factors or drivers affecting the global environment, particularly, greenhouse gas emissions (IPCC 2000). In the global climate change discussion, the Impact ***I*** could be one of the greenhouse gas emissions; if we are looking at the issue of energy security, then ***I*** could be energy consumption.

Waggoner and Ausubel (2002) use the "renovated" IPAT identity as a framework for sustainability science. They call it "ImPACT", and define various components as follows: ***I***, emissions, ***P***, population (capita), ***A***, affluence (GDP/capita), ***C***, intensity of use (energy/GDP), and ***T***, efficiency (emissions/energy). They further identify actors associated with each of these "levers" and discuss their role in attaining sustainability.

To frame the discussion of scenarios for the greenhouse gas emissions, IPCC (2000) uses the IPAT identity. It has also been widely used in estimating and analyzing emissions from energy related CO_2 emissions. In the various scenarios developed and analyzed by the IPCC, the long-term impact of the anthropogenic driving forces on greenhouse gas emissions have been identified with the help of the IPAT identity. One very popular formulation of the IPAT identity, known as the Kaya equation, has played a key role in shaping the debate in the global climate change realm (Ogawa 1991).

The Kaya identity is expressed as :

$$CO_2\ Emissions = Pop \times (GDP/Pop) \times (Energy/GDP) \times (CO_2/Energy)$$

where,

Pop = Population,

GDP = Gross Domestic Product.

On differentiating and then dividing both sides by the CO_2 emissions, we get the percent change in CO_2 emissions as a sum of percentage changes in the components of the right-hand side, i.e., population, per capita income, energy intensity, and carbon intensity. The multiplicative nature of the identity makes analysis simple and easy to understand, as the component growth rates can be shown to be additive.

Deitz and Rosa (1997) undertake a review of several models that investigate anthropogenic driving forces of environmental impact. They find that the IPAT equation is easily understood and can be very helpful in shaping discussion and thinking about various factors. The IPAT equation is only useful for the macro-level assessment, as regional and local drivers of environmental impacts are not included.

Impact (I)could be environmental degradation, energy consumption, or any other pertinent variable of interest. For example, Holdren (2000) uses it to decompose the energy consumption, as follows :

Energy Use = Population x (GDP/person) x (Energy/GDP); and

Carbon emissions = Population x (GDP/person) x (carbon intensity)

The IPAT identity is also a key identity in the field of industrial ecology. Chertow (2001) provides a detailed history of the origin of the IPAT identity and its variants over time.

Allen (2004) demonstrates the use of the IPAT identity as a framework to track national-scale material flows. In particular, he tracks SO_2 emission flows at the national scale to investigate the relative dominance of population and technology as key drivers. He concludes that IPAT gives a good starting point, but the real industrial systems are not as linear as suggested by the IPAT model. A linear causality model, which may be applicable for some pollutants that are directly dependent on the fuel types, may not be applicable to SO_x emissions.

In the next section, I develop the simulation model for estimating emissions from industrial sources.

5.2 Modeling Emissions from the Industrial Activity in the MCMA

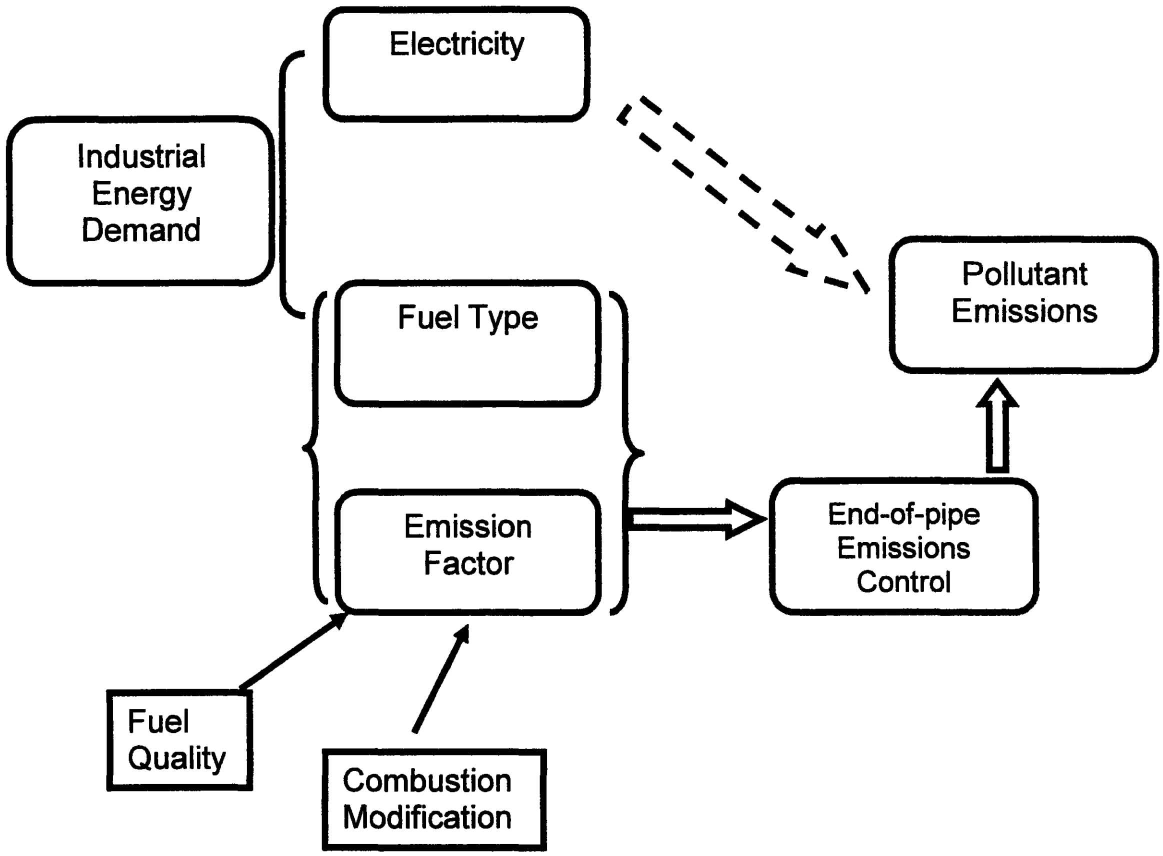
In this section, I identify various components affecting emissions from the industrial sources in the MCMA and use the IPAT framework to develop a simulation model to estimate pollutant emissions.

5.2.1 Factors Affecting Emissions from the Industrial Sector

Emissions from the industrial activities fall into three basic categories: combustion of fuels or consumption of energy, industrial processes or operations, and fugitive emissions, which are assumed to be relatively small compared to the first two categories. However, in certain sectors and industries, fugitive emissions make a large percentage of total emissions, such as in dry-cleaning, where hydrocarbon emissions are largely fugitive (Flores 2004).

The conceptual relationship among various factors affecting emissions of air pollution from industrial sources is depicted in Figure 5.1. Fuel type and combustion equipment affect emission rates, whereas the magnitude of industrial activity affects the rate of process and fugitive emissions. Modification of combustion process and installation of end-of-pipe control equipment for reducing specific pollutants also affect final emissions. Emissions released from a smokestack depend on the emission-removal efficiency of the control equipment, which is further dependent on the vintage of the equipment and its operation and maintenance.

Figure 5.1 The Factors Affecting Combustion-related Emissions from the Industrial Sources



The functional relationship between emissions from industrial sources and various parameters discussed above can be represented as follows:

$$EM_i\,(t) = f(IO, EI, EF_i, EC_i, CE_i\,)$$

$$EF_i = f(CFF)$$

$$CE_i = f\,(OM)$$

where,

EM_i = *Annual Emissions of pollutant i, in year t (tonne/year)*

IO = *Industrial Activity or Output (Pesos/year)*

EI = *Energy Intensity (Joule/Peso)*

EF_i = *Emission Factor for pollutant i(tonne/Joule)*

EC_i = *Population of Emission Controls for i (number)*

OM_i = *Operation and Maintenance for i*

CEi = *Control efficiency (%)*

CFF = *Clean Fuel Fraction = Energy supplied by gaseous fuels/Total Fossil-fuel supplied energy (fraction)*

To develop the simulation model for estimation of emissions from industries, I start with a fundamental identity and adapt it to incorporate various technology and policy parameters of interest.

I start with the following fundamental multiplicative identity:

Emissions = Activity x (Emissions/Activity),

or

$Emissions_i$ = Industrial Output x $Emissions_i$ per unit Output,

for all *i*, representing different air pollutants of interest.

$Emissions_i$ = Industrial Output x (Energy/Output) x ($Emission_i$ /Energy)

or

$Emissions_i$ = Industrial Output x Energy Intensity x Emission $Factor_i$

$$\boldsymbol{EM_i = IO * EI * EF_i} \tag{5.2}$$

where,

EM_i, IO, EI and EF_i are variables as defined above.

The multiplicative nature of the right hand side of the equation (5.2) allows us to derive a simple, yet powerful expression to explore and estimate the impact of the components of emissions. The simulation model, thus developed, can be put in the IPAT family of the models, where Impact ***I*** is represented by the emissions of a specific pollutant, ***P*** is represented by Industrial Output (in monetary terms), ***A*** can be energy intensity, and ***T*** can be thought as the emission factors.

Without loss of generality, we can drop subscript *i* and differentiate equation (5.2) to estimate the change in emissions for a given pollutant, as follows :

$$\Delta EM = \Delta IO.(EI.\ EF) + \Delta EI.(IO.EF) + \Delta EF(IO.EI) \qquad \textbf{(5.3)}$$

Dividing both sides by emissions *EM*,

$$\Delta EM / EM = (\Delta IO.(EI.\ EF) + \Delta EI.(IO.EF) + \Delta EF(IO.EI)) / EM$$

$$\Delta EM / EM = (\Delta IO / IO) + (\Delta EI / EI) + (\Delta EF / EF)$$

$$\%\Delta EM = \%\ \Delta IO + \%\ \Delta EI + \%\ \Delta EF \qquad \textbf{(5.4)}$$

Equation (5.4) states that in a given time period ***t***, the percent change in emissions is equal to the sum of the percent change in the three constituents, i.e., percent change in industrial output, energy intensity, and emission factors. For example, in a given period, a 3% change in the industrial output, -0.5% change in the energy intensity, and -1% change in the emissions factors would result in (3%-0.5%-1% = 1.5%) 1.5% increase in the emissions if there were no other variables, such as end-of-pipe controls, affecting the emissions.

Further, we can estimate emissions for period ***t+1*** as follows:

$$EM_{t+1} = EM_t + \Delta EM \qquad \textbf{(5.5)}$$

Therefore, if we know baseline emissions for a particular pollutant, *i*, we can estimate impact of the variation in industrial output, energy intensity, and emission factors on total annual emissions.

Now we look at the variables, industrial output, energy intensity, and emission factors. Note that Equation (5.5) does not take into account any end-of-pipe emission controls or any combustion modification. Therefore, the variable EM_t does not represent the actual emissions coming out of the stack, but emissions that would have been emitted had there been no control or combustion modification of any sort. Next, I incorporate combustion modifications and emission controls in the equation. The output emissions of a given pollutant, EM^O are given by –

$$EM^O_i, = EM_i * \mu_i * (1 - CE_i) \qquad \textbf{(5.6)}$$

where,

CE_i is control efficiency of the end-of-pipe emission control, for pollutant *i*.

μ_i is the combustion modification coefficient for pollutant *i*, defined as a ratio of emissions after combustion or process modification to the emissions before modifications.

EM^O_i is the quantity of pollutant *i* emitted in a given period, after incorporating combustion modification and implementing post-combustion controls.

Fuel switching (i.e., from diesel to natural gas) would also affect the emission factors and ultimately, the emissions coming out of the stack. To include the changes in the emission factors resulting from fuel-switching, I use a parameter called the *clean fuel fraction* (CFF), which is the ratio of clean (gaseous) fuel energy to total fuel energy, discussed in the following sub-section.

5.2.2 Fuel Switching and the Emission Factors

Let us assume that there are only two fuels under consideration, one gaseous and another liquid. In case of the Mexico City's industrial sector, the gaseous fuel is natural gas, and the liquid fuel is industrial diesel. I define *clean fuel fraction* (CFF), as ratio of heat supplied by the gaseous fuel to total heat input to the industrial sector. Let the initial weighted emission factor be, EF_1, and after fuel switching, the weighted emission factor be EF_2. We can express emission factors as :

$$EF_1 = (F_{g1} \cdot EF_g + F_{d1} \cdot EF_d)/(F_{g1}+F_{d1}) \qquad \textbf{(5.7)}$$

$$EF_2 = (F_{g2} \cdot EF_g + F_{d2} \cdot EF_d)/(F_{g2}+F_{d2}) \qquad \textbf{(5.8)}$$

where,

Fg = Gaseous fuel consumed (Joules)

Fd = Liquid fuel consumed (Joules)

EF_g = Emission factor for gaseous fuel (tonne/Joule)

EF_d = Emission factor for industrial diesel (tonne/Joule)

We assume that total heat input remains constant and that only the composition of the total energy supply changes. Therefore, we can write :

$$F = (F_{g1}+F_{d1}) = (F_{g2}+F_{d2}) \qquad \textbf{(5.9)}$$

Change in emission factor,

$$\Delta EF = EF_2 - EF_1 \qquad \textbf{(5.10)}$$

or

$$\Delta EF = ((F_{g2} \cdot EF_g + F_{d2} \cdot EF_d) - (F_{g1} \cdot EF_g + F_{d1} \cdot EF_d))/F \qquad \textbf{(5.11)}$$

Or, using (5.9) above, we can write -

$$\Delta EF = (CFF_2 - CFF_1).(EF_g - EF_d) \qquad \textbf{(5.12)}$$

where,

$$CFF = F_g/(F_g+F_d) \qquad \textbf{(5.13)}$$

CFF_2 is the clean fuel fraction after fuel switching and CFF_1 is the clean fuel fraction before fuel switching. The change in emissions factor can be expressed as :

$$\Delta EF = \Delta CFF * (EF_g - EF_d) \qquad \textbf{(5.14)}$$

Thus for a given change in the clean fuel fraction, we can estimate the change in emission factors and incorporate the change into Equation (5.4) to estimate emissions as a result of a change in the *clean fuel fraction.*

5.3 A Critical Review of the Model

As noted by many researchers the IPAT identity is a powerful tool to understand the relationship of various driver components and to identify the role that policy handles can play in mitigating any negative impacts.

Although the IPAT identity has been very widely used owing to its simplicity; it has also attracted a fair share of criticism. Dietz and Roza (1998) criticise the level of decomposition of the forces of environmental change to be too simplistic and that the IPAT formulation does not allow for interaction among various factors.

Most of the criticisms stem from its simplicity. The model assumes a linear relationship of the Impact ***I***, with the right hand side components and does not take into account non-linear interactions among these components. For example, according to the IPAT identity, if the population is doubled, *ceteris paribus*, the emissions or energy consumption would also double. This kind of linear relationship does not exist in reality. Moreover, in several instances, say, in the case of emissions from households, population as a unit of analysis is not as important, as say the number of households (Roth 2003). Because energy consumption by a household is a function of the average size of the household, the number of households is a better indicator for estimating energy demand than the number of people.

IPCC (2000) recognizes the limitations of the model based on the IPAT identity, and states (pp 105) -

> While the Kaya identity can be used to organize discussion of the primary driving forces of CO_2 emissions, but the four terms on the right hand side are neither fundamental driving force in themselves, nor as generally independent from each other.
>
> ...
>
> At face value the IPAT and Kaya identities suggest that CO_2 emissions grow linearly with population increase, this depends on the real (or modeled) interactions between demographics and economic growth and on those between technology, economic structure, and affluence. In principle, such interactions preclude a simple linear interpretation of the role of population growth in emissions.

Similarly, for the case of industrial emissions, Equation (5.2) suggests that doubling the industrial output would double emissions of pollutants. This does not take into account any economies of scale that may exist, resulting in a non-linear relationship between the independent and dependent variables. Moreover, at a practical level, there are at least two ways to increase the level of industrial output: by increasing the utilization of the existing capacity, and by augmenting the production capacity by installation of new production equipment. Which one of these two approaches to increase production is adopted by the industrial sector would have a significant impact on the emissions. For example, if the output is doubled from newer and cleaner facilities, the emissions will not be double the original level. The existing form of the model does not capture such details about implementation.

The variable energy intensity, *EI*, enables an analyst to capture the change in the energy needed to produce unit goods, in monetary terms. Changes in the structure of the industrial sector, where one kind of manufacturing activity is replaced by another low energy intensity manufacturing activity or there is a change in the process of manufacturing resulting in the changes in energy intensity, both are embedded in the variable *EI*. This lumping of the two effects, i.e., change in structure, and/or change in technology, can be decomposed using available decomposition methods, such as one used by Gallagher (2004) for the Mexican industries. To address this shortcoming of the model, I have used Structure Adjusted Energy Intensity (SAEI), which takes into account changes in the industrial structure over time and incorporating changes in the energy intensity at the sub-sector level (see Section 5.4.3 for more details). Moreover, the increase in energy intensity may not necessarily increase the emissions proportionally, as technology change may warrant change in the energy intensity and fuel switching at the same time (moving from blast furnace to induction furnace is an example of switching from conventional fossil-fuel to electricity, as well as a change in the energy intensity due to the change in the process simultaneously).

A weighted average value of the emission factor, *EF*, gives sufficiently accurate values at the aggregate level. However, the change in the emission factors, ΔEF, is assumed to be a function of the fuel type alone, but the type and size of the combustion equipment in each industrial installation can result in different emissions for specific pollutants. For example, diesel burnt in a reciprocating engine would result in higher NO_x emissions than fuel burnt in a rotary turbine (Vijay 2004).

As stated earlier, the original formulation of the model, after the IPAT identity, as represented by Equation (5.4) does not incorporate impact of combustion modification or end-of-pipe-controls for specific pollutants. However, this shortcoming of the original formulation is easy to rectify, as shown in Equation (5.6).

5.4 The Model Parameters

In this section, I discuss the model parameters and how they are incorporated in the model to estimate energy demand and air pollution.

5.4.1 Industrial Activity or Output

Industrial activity is measured in terms of physical quantity of output, e.g., number of cars produced in a year, or in monetary values, i.e., dollar value of the production in a given year. Since I modeled the industrial sector as a whole, for the purpose of scenario analysis, monetary value of output is a better indicator of the industrial activity. In the partial equilibrium framework, the industrial activity *IA* can be represented as a function of two independent variables, one exogenous to the model and another endogenous. The exogenous component is the one that depends on the macroeconomic environment and is treated as given for the purpose of this model. The other component affecting industrial output is a policy variable, which affects output of industries in the MCMA because of direct policy intervention, such as incentives to move production to geographical areas outside the valley or increased excise taxes etc.

The exogenous component affecting the industrial output is the annual growth rate of the industrial sector corresponding to different Future Stories (see Chapter 4). The policy variable affecting activity level or output is modeled to affect the exogenous rate of growth and is discussed in detail in Chapter 7.

5.4.2 Energy Intensity

Energy intensity is defined as energy consumed per unit of output, where output is defined in monetary terms. Baseline energy intensity values for the Mexican economy are obtained from the Mexican Energy Balance (SENER 2003). However, the sub-sector level energy intensity values needed for modeling the impact of the structural shift in industry are estimated on the basis of sub-sector energy intensity estimates for the US manufacturing sector (EIA 1995).

5.4.3 The Structure of the Industrial Sector

Equation (5.4) does not take into account the shift in the structure of the industry over time. To capture the impact of the structural shift, I introduce the variable, Structurally Adjusted Energy Intensity (SAEI), which is defined in this sub-section. Chapter 7 discusses specifics of the structural shift in the industrial sector of the MCMA and its implications on energy demand and emissions.

The structure of the industry is defined by the share of its constituent industry sub-sectors. Let there be n sub-sectors in the industrial sector, for example, chemical industry, metal products, non-metallic minerals, etc. If output of each sub-sector, in a given period is S_j, then the total industrial output is depicted as follows :

IO (t) = ΣSj, for all sectors j = 1 to n.

Then, the structure is defined by the elements of the matrix, **S**, as follows:

S = [sj], where sj = Sj/ ΣSj,

Further, if the energy intensity of each of the sub-sector is *EIj*, and the elements of the matrix **EI** represent energy intensity of each industry sub-sector, then we can express structure adjusted energy intensity of the industry as follows :

SAEI (t) = $[\mathbf{EI}]^{T}.[\mathbf{S}]$;

where,

$[\mathbf{EI}]^{T}$ is the transpose of the column matrix [**EI**]

[**S**] is the column matrix indicating structure of the industrial sector.

If we replace energy intensity *EI* in Equation 5.4 with structure adjusted energy intensity, SAEI, the new estimates of emissions will also capture any changes in the structure of the industrial sector and sub-sectoral energy intensity that may take place in the model period. The modified equation will be as follows :

$$\% \Delta EM = \% \Delta IO + \% \Delta SAEI + \% \Delta EF \quad \textbf{(5.15)}$$

5.5 The Target Pollutants and Emission Factors

Emission factors for a given pollutant for different fuels are taken from the United States Environmental Protection Agency (USEPA)'s AP-42. For NO_x emissions from power generation in the MCMA, emission factors are estimated on the basis of actual emissions reported for two base-load power plants. Wherever necessary, emission factors were calibrated on the basis of the reported industrial fuel consumption and emissions from the industrial sectors, as reported in the emissions inventory for 2000.

For modeling of the emissions for the period 2001-2025, we have used emissions and corresponding emission factors for the year 2000. For the industrial sector, PM_{10}, SO_2, and NO_x are identified as target local pollutants for identifying abatement options, as discussed in the following sub-section.

5.5.1 The Target pollutants

In Chapter 3, I presented the emissions from the emissions inventory for the Mexico City Metropolitan Area (MCMA) for the year 2000. The industrial and power sector contributed 14.1% of NO_x (represented as NO_2), 70.2% of SO_2, 3.5% of hydrocarbons, 0.6% of carbon monoxides, and 29 % of PM_{10} emissions (SMA 2004).

Carbon monoxide emissions from the industrial and power sector contribute less than 1% of the total CO emissions in the MCMA, and are dominated by emissions from mobile sources. Nitrogen oxides play an important role in formation of ground level ozone in the MCMA. Hydrocarbons are also important precursors to ozone formation, although ozone formation in the MCMA is understood to be NO_x limited (Molina and Molina 2002). Sulfur oxides are created in industrial processes and from the combustion of sulfur contained in the fuel. Particulate matter is formed due to combustion of fossil fuels, or it results from industrial processes.

We focus on modeling and estimating NO_x, SO_2 and PM_{10} emissions from the industrial sector. Baseline emissions for the pollutants of interest, i.e., NO_x, SO_2, PM_{10}, hydrocarbons, and carbon monoxide are obtained from the emissions inventory for the MCMA for the year 2000 (SMA 2004).

5.5.2 Emission Factors for SO_2

SO_x is the name given to family of pollutants that includes SO_2 and SO_3. Sulfur is relatively inert and harmless in its elemental state. All fuels contain some sulfur. Fuels such as wood or natural gas have very little sulfur (less than 0.1 %), whereas certain type of coal can have very high sulfur content (up to 4%). Emissions of SO_x often result from oxidation of elemental sulfur in the fossil fuels during combustion. Other important sources of sulfur in the environment are the processing of sulfur-bearing ores and volcanic activity. SO_x, when it comes in contact with moisture, gets converted into sulfuric acid, and the rate of conversion from SO_x to acid depends on the moisture content of atmosphere. SO_x emissions have been identified as the principle cause of acid rain. When acid comes in contact with appropriate cations in the atmosphere, it gets converted in sulfates, which are small particles generally of size (0.1-to-1 micron). Thus, SO_x emissions also act as precursor to $PM_{2.5}$ concentration in the atmosphere. It is estimated that about 50% or more of the $PM_{2.5}$ comes from secondary sources, such as conversion of NO_x and SO_x in sulfate or nitrate particles of small size. Impacts of SO_x on property and vegetation have been recorded. Historical monuments are prone to damage from acid deposition. In a recent court order, Supreme Court in India ordered the Government to close or move a refinery located near the famous monument the Taj Mahal due to evidence of damage from SO_x emissions from the refinery. The health impacts of SO_2 concentration have been studied in many epidemiological studies. Asthma, chronic bronchitis, and lower respiratory disease have been associated with high concentrations of SO_2. It is not yet clear if SO_2 is the only biologically active agent. There is substantial evidence to suggest that aerosols, which are created by deposition of sulfuric acid on fine particles, are a strong biological agent and adversely impact human health.

SO_x emission factors are directly dependent on the sulfur content of the fuel in question. The dominant source of sulfur in the MCMA industrial sector is the sulfur contained in the industrial diesel. A large share of total emissions of SO_x (about 50% for the MCMA industrial sector) comes from the chemical process industrial sector (COA 2003).

5.5.3 Formation of NO_x and Emission Factors

Formation of NO_x in the combustion process is a result of a mechanism known as *Zeldovich* mechanism. Nitrogen forms about eight oxides, but from the local and regional air pollution point of view, the following two are considered important, nitric oxide (NO) and nitrogen dioxide (NO_2). In the combustion process, primarily NO is formed. NO is generated to the limit of available oxygen (about 200,000 ppm) in air at temperatures above 1300C. At temperatures below 760C NO is generated in much lower concentrations, or not at all.

The following reactions show a simplified version of the *Zeldovich* mechanism that explains the formation of NO during combustion process.

Figure 5.2 Formation of NO_x - the Zeldovich Mechanism

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

Besides NO production from lightening and soil, production of NO is largely anthropogenic, only about 10% is biogenic (Nevers 1995). NO is similar to CO in its health impact, resulting in the failure of the blood to absorb oxygen. However, it is only slightly soluble and therefore not a threat to human health, except to infants and sensitive people. NO_2 concentration is used as a surrogate of NO_x, as it is a precursor of ozone. The three ways NO_x is produced in combustion process are listed below.

1. **Thermal NO_x** - This is the most prominent pathway of NO_x formation in the combustion process, usually in the presence of excess air. The nitrogen content in the air is oxidized at high temperature (formed between 760-1300C and above, in air-rich atmosphere) and results in NO_x formation.

2. **Fuel NO_x** – In fuels that contain nitrogen NO_x is produced on combustion by the oxidation of organic nitrogen bound in the fuel.

3. **Prompt NO_x** - Formed from oxidation of molecular nitrogen in air, in fuel-rich conditions, similar to fuel NO_x and unlike the thermal NO_x which is formed in presence of excess air. The abundance of prompt NO_x is disputed.

NO_x reacts with the moisture in the same way as that of SO_x, and forms nitric acid, responsible for acid rain. Another important environmental impact of NO_x in the atmosphere is its role in the formation of urban smog and ground level ozone. A complex photochemical reaction prompts formation of tropospheric ozone, in the presence of hydrocarbons and sunlight. Ozone has been widely recognized as a very reactive gas responsible for irritation, respiratory problems, watering of eyes, etc. NO_2 is one of the exceptional pollutants, in that most other gaseous pollutants are totally transparent. Urban smog appears to be brown due to the presence of NO_2.

The primary and secondary national air-quality standard for NO_2 in the US is 0.053 ppm or 100 micrograms per cubic meter, annual arithmetic mean concentration.

Other problems associated with NO_x are eutrophication, the problem of nutrient enrichment, that occurs in water bodies if the availability of either nitrate or phosphate becomes too large. In eutrophication, the natural ratio of nutrients is altered, resulting in a misbalance in the ecosystem, leading to algal blooms which deplete the oxygen content of the water. The phenomenon of eutrophication can make deeper waters inhabitable for plant and animal life.

Emission factors for NO_x depend on the fuel type and the combustion equipment used. For industrial applications in the MCMA, most of the NO_x is produced by the combustion of natural gas and industrial diesel in conventional boilers to generate process heat.

5.5.4 Emission Factors for CO_2

CO_2 is an important greenhouse gas. Although this analysis is focused on local emissions, CO_2 emissions are also estimated for all the scenarios. Assuming complete combustion of fuels, and conversion of the entire carbon in the fuel to carbon dioxide; the emission factors for CO_2 can be estimated from the carbon content in the fuel. The emissions of CO_2 can be easily estimated if the fuel composition is known. We use standard emission factors for CO_2 for different fuels from IPCC, INE and USEPA's AP-42.

5.5.5 Emission Factors for PM_{10}

Emissions of PM from the industrial sector come from three sources, the combustion of fuels, industrial processes and the fugitive emissions. The emission factors for PM_{10} owing to combustion of fuels for diesel and natural gas were taken from the USAPA's AP-42. The emission factors from industrial processes were assumed to be directly proportional to the industrial output from the industrial sector in a given year. In this study, the fugitive emissions were not specifically included in the modeling.

5.5.6 Emission Factors for Hydrocarbons

Since target pollutants from the industrial sources are NO_x, PM_{10} and SO_x, the emissions estimations for non-methane hydrocarbons are not included in this study.

5.6 Summary and Conclusions

In this chapter, I presented the factors affecting the emissions and outlined the emissions estimation model which takes into account variables, such as structural change, energy intensity, and end-of-pipe controls such as low-NO_x burner or fabric-filter for PM emissions control.

The model is based on the IPAT identity, and as such does not take into account the non-linear interactions among the variables of interest. However, the model provides a simple framework to estimate emissions and carry out policy analysis.

In the next chapter, I use macroeconomic indicators of the industrial growth for the three Future Stories (see Chapter 4), energy intensity, and variation in the structure of the MCMA industry to estimate energy demand from the manufacturing sector for the period 2000-2025.

Chapter 6

Structural Shift in the MCMA Manufacturing Sector: Implications for Energy Demand and Air Pollution

Energy consumption is the primary driver of combustion related air pollutant emissions from industrial sources. Therefore, in order to analyze implications of fuel-energy consumption on air pollution, first I investigate the role of the factors affecting industrial energy demand in the MCMA. In particular, in this chapter, I develop scenarios of industrial energy-demand resulting from combination of different values of the following three variables: energy intensity, structure of the MCMA industry, and industrial growth rate. The energy demand scenarios analyzed in this chapter present the limitations of achieving emissions abatement goals by managing energy demand alone, and provide a framework for a more detailed analysis of the end-of-pipe and process control options, discussed and analyzed in the next chapter.

In Chapter 5, I developed a model for estimating energy demand and emissions from the industrial sources of air pollution in the MCMA. I also briefly discussed implication of a structural shift in the industry on energy demand. In this chapter, I portray the structure of the industrial sector in the MCMA. Then I outline recent changes in the structure of the MCMA industrial sector, by analyzing relative shifts in the shares of different sub-sectors in the total regional industrial output. I then estimate the industrial energy demand for the MCMA, and analyze the implications of structural shift, the growth of industrial output, and changes in the energy intensity on the MCMA industrial energy demand. The next chapter focuses on estimating the emissions and carrying out a multi-attribute tradeoff analysis to identify robust strategies for air-pollution abatement.

Section 6.1 outlines the factors affecting the industrial energy demand, and surveys the published research on decomposition of Mexican energy demand. Section 6.2 explains the role of industrial structure in estimating energy demand, and Section 6.3 characterizes the industrial sector in the MCMA. Section 6.4 outlines the structure of industry in the DF, EM, and MCMA. Further this section analyzes the recent trends in the structural shift in the MCMA industry (1995-2003). Section 6.5 deals with energy consumption and presents energy-intensity estimates of four sub-sectors -- chemical, food & beverages, metal products and other manufacturing -- of the MCMA industry. In Section 6.6, I present results of energy demand estimations for various scenarios, analyze the changes in energy demand for the MCMA industry, and discuss its implications for the air pollution. Section 6.7 outlines policy implications of analysis of the MCMA industrial energy-demand scenarios, and Section 6.8 concludes the chapter with a summary.

6.1 Factors Affecting Energy Demand

The total output or activity level of a sector (sometimes also known as the scale-effect, see Gallagher (2004) for example), energy intensity of the sub-sectors, and the share of the sub-sectors in the total output are three main factors affecting the energy demand. Figure 6.1 illustrates the relationship among these factors. I also discussed this relationship in Section 5.4, and related the structure adjusted energy intensity with the emissions, in equation (5.15).

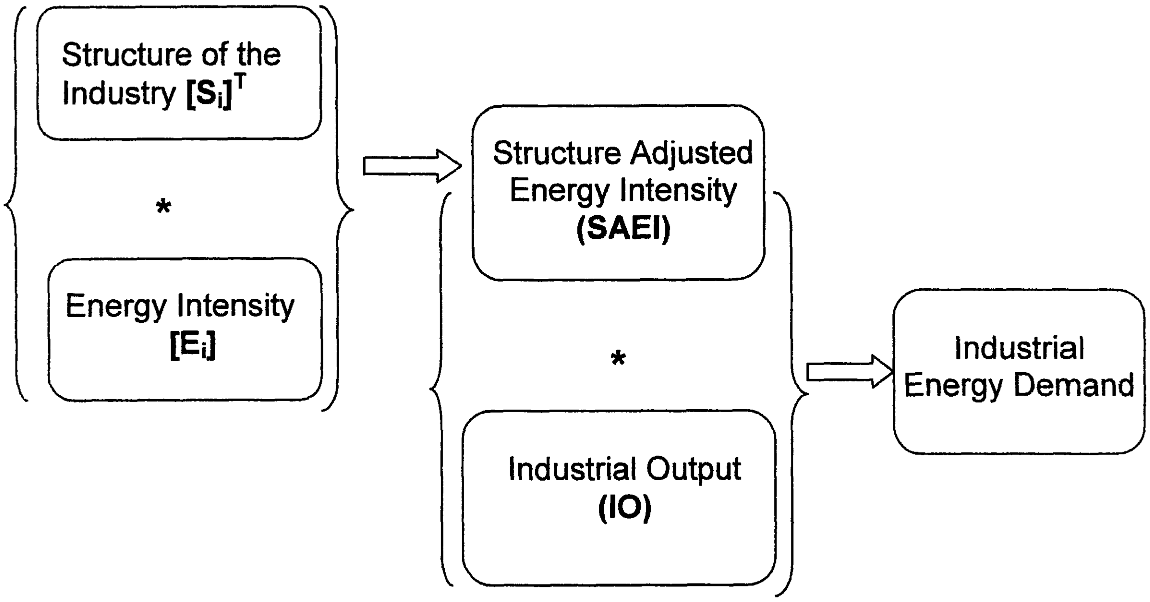
In the energy and regional economics literature, analysts have proposed and used several decomposition[1] methods to understand the nature of total energy demand by various sectors (see IEA 2004; Polenske and Lin 1993). The

[1] The decomposition methods used in the regional economics literature is called as shift-share analysis, as the method was originally developed and used to analyze the impacts of shift of the industry-mix on employment in a given region (see Lin 1992; Polenske and Lin 1993).

decomposition methods, based on Laspeyers index, Divisia index, or a variant of these, provide a quantitative measure of the various factors affecting the changes in the aggregate energy demand (Ang and Liu 2001). Although initially used for identifying the relative contribution of variables affecting the total energy demand, recently the decomposition methods have found wide applications in estimating relative contribution of various factors to the greenhouse gas emissions (for example, see Sheinbaum 1998; IEA 2004). Ang (2000) has conducted an extensive survey and review of the energy decomposition methods used in the energy and environmental studies. Recently, there has been an increase in the number of studies that analyze the environmental impacts of energy consumption, specifically, greenhouse gas emissions. Decomposition of energy-related air pollutant emissions is an extension of analysis of the factors affecting energy demand. The emissions of pollutants from energy use are estimated by multiplying energy consumption of fuels by their respective emission factors (Ang 2000). The extension of the methodology from energy demand to air-pollutant emissions is straight-forward, as far greenhouse gas emissions from fuels is concerned. However, estimating emissions, such as NO_x, which are formed as part of the combustion process and depend on several other variables, such as combustion configuration, combustion temperature, etc., add to uncertainty in estimations.

Glovoe and Schipper (1996) have used the decomposition analysis to identify the structural shifts and changes in the energy intensity in the US manufacturing industry. Further, they have also incorporated changes in the fuel-mix to estimate the CO_2 emissions from the US manufacturing sector.

Figure 6.1 Estimating Structure Adjusted Industrial Energy Demand



Polenske and Lin(1992) have analyzed the shift in the Chinese energy demand using share-shift analysis for the period 1980-1988, when the energy intensity declined by 30% in China. They use shift-share technique and quantify the factors affecting decline in the energy intensity in Chinese industry. They criticize the technique in that it is an accounting identity and does not capture any behavioral changes that may occur over time due to various policy initiatives. However, they also articulate the usefulness of this technique in estimating future energy demand and providing insight to the policymakers about energy-demand impacts of the future direction of the industrial policy.

6.1.1 Decomposition of Energy Demand in Mexican Industry

In the past, Mexico specific energy-demand studies have focused on decomposition of the energy consumption to identify the output effect (also known as scale-effect), structure effect (also known as industry-mix effect), and intensity effect (Sterner 1985). The output effect is the effect of changes of scale in the production, while the industrial energy intensity and the industry-mix remain constant. The structure effect captures the shift in the shares of various industry sub-sectors on total energy demand, and the intensity effect captures the impact of the changes in the energy intensity of sub-sectors over the study period on total energy demand.

Recent Mexico specific studies have looked at the changes in the Mexican energy demand in relation to the greenhouse gas emissions. Sheinbaum and Rodríguez (1997) analyzed the energy consumption by the Mexican manufacturing sector between 1987 and 1993. They noted that during the study period, carbon dioxide emissions from industrial primary energy use increased by only 2%, while the real value added increased by 22%. They found that the energy-intensity changes in some sub-sectors, specifically, iron and steel, chemical, as well as pulp and paper, have played a key role in the overall reduction in energy consumption. Further, during this period, the manufacturing sector's CO_2 intensity declined by 16%, which was a direct result of reductions achieved in the energy intensity of different sub-sectors.

Sheinbaum and Ozawa (1998) analyzed the energy demand for the cement industry, focusing on the changes in the product-mix in the Mexican cement industry and its impact on energy consumption and the CO_2 emissions. They found that, along with the changes in real energy intensity and fuel-mix, changes in the product-mix also played a key role in reducing greenhouse gas emissions from the cement industry from 1982 to 1994.

Aguayo and Gallagher (2004) examine the energy-intensity trend in the Mexican industry for a period 1988-1998. They find that a decline in the energy intensity in the Mexican economy began in 1988. They also find that Mexican energy consumption per unit of GDP is driven by the reduction in energy intensity. They attribute the reduction in the energy intensity to the changes in the industrial structure and technology. Their analysis indicates that energy-intensity decline during the period 1988-1998 was highest in aluminum production, iron and steel, and paper and pulp industry.

Although the MCMA industrial sector is a major contributor to the total manufacturing output in the country, I did not find any study specific to the MCMA, which investigates impact of various factors on energy demand or air pollution from the manufacturing sector.

6.2 Energy Demand and Structure of the MCMA Industry

Energy consumption related air pollution is a function of the total energy consumption, and the fuel-mix[2]. The economic growth of the MCMA region would translate into an increase in demand for goods and services. The manufacturing and informal sectors in the MCMA can respond to the increased demand by increasing imports, increasing regional production, or by doing both. The energy demand from the non-transport sources depends on the change in the output, as reflected by the macroeconomic indicators of the three Future Stories (i.e., Growth Unbound, Changing Climates, and Divided City, see Chapter 4 for detailed descriptions of the Future Stories). Further, the structure of the manufacturing sector in the region could also change over time. The structure of the industry is represented by the relative share of various sub-sectors of the economy of the region. Energy intensity of the chemical sub-sector is higher than that of the metal products industry (see Table 6.5). Therefore, if the structure of the manufacturing industry in the MCMA were to change in such a way that the relative dominance of the chemical industry continues, this would affect the energy demand by the manufacturing sector as whole. The change in the energy intensity is another important variable that would affect the

[2] Several other factors affect quantity of air pollution, such as combustion type, combustion temperature, efficiency of control equipment, etc. I will discuss the impact of these factors on air pollution in the next chapter.

magnitude of the energy demand in the MCMA. The International Energy Agency (IEA 2004) has reported the manufacturing sector energy intensity for its member countries declined at an average rate of 3.2% per annum, between 1973 and 1986, but only 0.5% per annum from 1987 to 1999. The rate of change of energy intensity -- moderate or fast -- would significantly affect the energy demand from the manufacturing sector. The next section characterizes the manufacturing sector in the MCMA, in terms of the shares of various industries in the total output and employment.

6.3 Characteristics of the Manufacturing Sector in the MCMA

The manufacturing sector in the MCMA consists of the manufacturing units in the delegations (*delegaciones*) of the Federal District (*Distrito Federal* or DF) and municipalities (*municipios*) in the urban part of the State of Mexico (*Estado de Mexico* or EM). According to the economic census (INEGI 1999), there were 31,068 economic units[3] in the DF, belonging to the manufacturing industry. In the EM, the census reported 35,318 units engaged in the manufacturing activity. Of more than 35,000 units in the EM, 25,362 were located in the urban part of the EM, i.e., were located in the 37 municipalities included in the definition of the MCMA. Therefore, the total number of economic units in the MCMA engaged in the manufacturing activity was 56,430.

The manufacturing sector in the DF employed about half a million people, and contributed 210.6 billion pesos to the national economy in the year 1998. In the same period, the manufacturing sector in the EM provided jobs to about ten thousand fewer people, than that in the DF, and added 267 billion pesos to the national

[3] INEGI (1999) defines an economic unit or establishment as - "... that [is] physically in a single location, written down in a permanent way and delimited by constructions, combines actions and resources under the control of a proprietary single company and controller, to carry out goods production activities, assembly, excavations, works of construction, buying and selling of merchandise or installment of services, extraction of minerals, with some commercial end or not".

economy. The manufacturing sector in the EM exhibited higher productivity than that in the DF. Probably, this is due to the fact that newer industries in the EM are more productive than the older industries in the DF.

In Mexico, there were 344,118 economic units in the manufacturing sector. Therefore, about one-sixth of the nation's manufacturing facilities were concentrated in the MCMA region. The manufacturing industry located in the MCMA region contributed one-quarter of the total value added by the manufacturing industry in Mexico.

6.3.1 Productivity of the Manufacturing Sector

The 344,000 units in the manufacturing sector in Mexico added 1.65 trillion pesos to the economy, and employed 4.23 million people. Thus, productivity of the manufacturing sector at the national level was 390,000 pesos per person, whereas in the DF, the productivity was 423,000 pesos per person, and in the EM, the manufacturing industry added 546,000 pesos per person employed by the sector. The productivity of manufacturing sector in the DF is higher than that of average Mexican productivity, but lower than that of the EM industry. The manufacturing sector in the EM has added many new industrial establishments in the recent past. Therefore, the plant-vintage is a probable cause of lower productivity of the DF industries, as compared to the EM.

The manufacturing sector in the MCMA plays an important role in the economy of the region. It produces 24% of the total national manufacturing sector output, provides jobs to 20% of the total people employed in the sector in Mexico, and houses about 16% of the nation's the manufacturing capability (Table 6.1). Therefore, socio-economic implications of designing the environmental policies for the manufacturing sector are very important.

Table 6.1 Industrial Output, Number of Establishments, and Productivity in the DF, EM, MCMA and Mexico (1998)

Region	No of Industries		Industrial Output		Persons Employed		Productivity	
	Number	%	(billion pesos)	%	(thousand)	%	tppp	% Δ
DF	31,068	9	211	13	498	12	423	8.5
EM	35,318	10	267	16	489	12	546	40.0
MCMA	56,430	16	402	24	849	20	474	21.5
Mexico	344,118	100	1,650	100	4,232	100	390	NA

tppp = Thousand Pesos Per Person

Source: Author's estimates based on data from INEGI - Censos Económicos 1999

6.3.2 Classification of the Manufacturing Sector

The manufacturing sector consists of several sub-sectors. There are two different classifications used by the *Instituto Nacional de Estadística, Geográfica y Informática* (INEGI) to report the economic census data. The first is *Clasificación Mexicana de Actividades y Productos* (CMAP), in which, code 3 of the classification refers to the manufacturing industry, which is further subdivided into 9 sub-sectors, at the two-digit level of classification, as shown in Table 6.2.

The second classification is known as *Sistema de Clasificación Industrial de America del Norte* (SCIAN)[4]. Although SCIAN is a newer classification system, the air-pollution inventory for the MCMA for year 2000 uses the CMAP classification of the manufacturing industry sub-sectors to report air-pollution data (Table 6.2) from the

[4] *Sistema de Clasificación Industrial de America del Norte* (SCIAN) is a result of an effort to develop a common classification system by the US, Mexico and Canada.

Table 6.2 CMAP Classification of the MCMA Manufacturing Sector and Sub-sector Emissions (2000)

ISIC	Sector	NO_x (t/y)	NO_x %	PM_{10} (t/y)	PM_{10} %	SO_2 (t/y)	SO_2 %
36	Non-Metallic Minerals	4350	33.2	256	9.8	768	7.5
35	Chemicals, Rubber, Plastics, etc.	2311	17.7	394	15.1	2332	22.7
38	Metal-products & Machinery	1441	11.0	374	14.3	973	9.5
32	Clothing, Textiles, etc.	1307	10.0	350	13.4	2213	21.5
34	Paper, Paper, Publishing, etc.	1194	9.1	163	6.3	1793	17.5
31	Food, Beverages, & Tobacco	1130	8.6	366	14.0	1109	10.8
37	Basic Metal Industries	1122	8.6	513	19.7	615	6.0
39	Other Manufacturing Industries	166	1.3	61	2.3	229	2.2
33	Wood and Wood products	70	0.5	130	5.0	240	2.3
	Total	**13,091**	100	**2,607**	100	**10,272**	100

t/y = Tonne/Year
ISIC = International Standard Industrial Classification
PM_{10} = Particulate Matter smaller than 10 microgram
SO_2 = Sulfur dioxide
NO_x = Oxides of Nitrogen, generally represented as NO_2
HC = Hydrocarbons
Source: Emissions Inventory for the MCMA for 2000 (SMA 2004)

manufacturing sector. Further, the abatement-cost data, reported by Hartman et al. (1994) uses the same categorization as that of CMAP. My model and analysis of the manufacturing industry-sector -- to analyze implications of growth and other parameters on air pollution -- draws heavily upon the emissions inventory and the abatement-cost data. Therefore, I have chosen to use the CMAP classification of the manufacturing industry for the analysis.

6.3.3 The Structure of the Manufacturing Sector in the MCMA

The structure of the manufacturing sector is defined by the relative share of its constituent sub-sectors, in the total output by the sector. Let the monetary value of output by a sub-sector *i* in a given year be S_i, the total value of output by all the sub-sectors be represented by S;

$S = \Sigma S_i$ for all sub-sectors i.

The structure of the industry sector can be represented by a vector S_i^T, where each element of the vector is a ratio of output by the sub-sector, to the total output in monetary terms in a given year, or, each element, $s_i = S_i/(\Sigma S_i)$

The structure of the industry in the DF, EM, and the MCMA is shown by the relative contribution of the sub-sectors, in Table 6.3. The structure of the manufacturing industry in the DF is dominated by the chemical industry (CMAC code 35), with a 33% share in the output, followed by the metal-products, machinery and equipment (CMAC code 38), and food, beverages, and tobacco industry (CMAC code 31), with a share of 20% in the total manufacturing sector output in the DF.

Table 6.3 Structure of the manufacturing sector in DF, EM, and the MCMA (1998)

Code	Industry Name	DF	EM[1]	MCMA[2]
35	Chemicals, petroleum, coal, rubber, and plastic derivatives	0.33	0.23	0.28
38	Metal-products, machinery, and equipment	0.21	0.30	0.25
31	Food products, beverages, and tobacco	0.20	0.23	0.21
32	Clothing and textiles, and leather industry	0.10	0.09	0.10
34	Paper and paper, printing, and editorial products	0.10	0.06	0.08
36	Non-metallic mineral products	0.01	0.05	0.03
33	Wood industry and wood products	0.02	0.02	0.02
37	Basic metal industries	0.02	0.03	0.02
39	Other manufacturing industries	0.01	0.01	0.01

Notes:

1. Calculated on the basis of the output from the industries in the State of Mexico.

2. Output from the MCMA includes 16 delegations and 37 municipalities, as defined by Molina and Molina (2002).

Source: Calculated by the author, using data from the economic census, INEGI (2003)

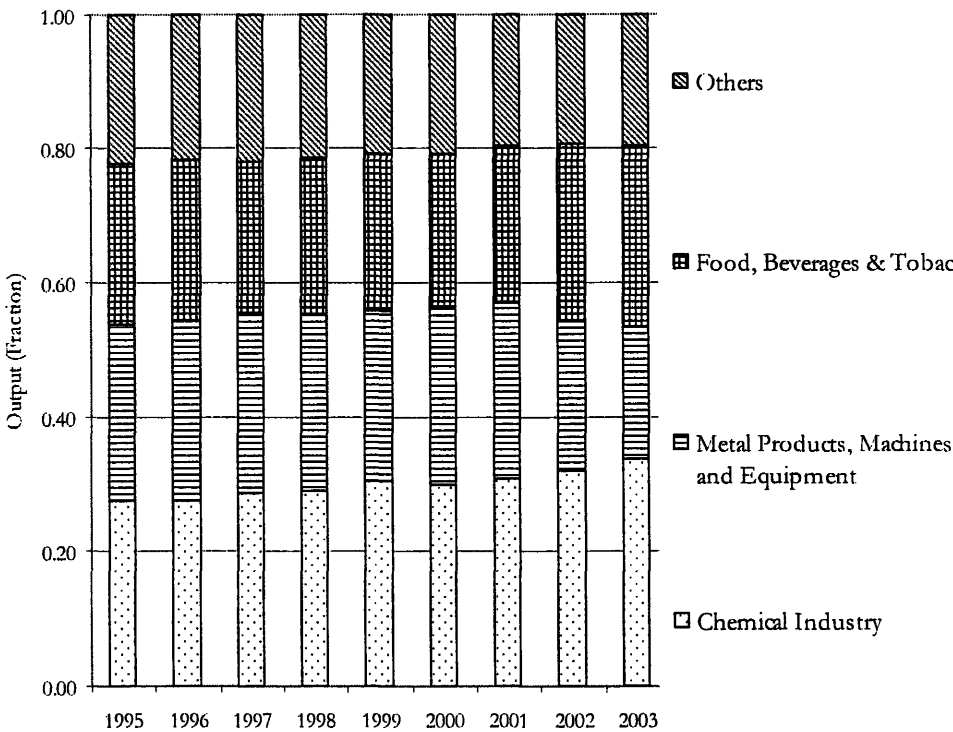
Thus, the chemical industry plays a dominant role in the industrial landscape of the DF. Output data from the EM for the same year indicates that the chemical industry is a dominant player in the EM as well. However, the metallic industry's share is largest (30%) in the EM, followed by the chemical industry with 23% share. The food and beverages industry contributes 23% of output in the EM. We see that the DF is a chemical industry dominated region, whereas the EM is dominated by the metal-products, machinery, and equipment industry.

When we combine the DF and EM data, to estimate output from different industries in the MCMA, we find that chemical, metal-products, and food and beverages are the three most dominant industries, producing about 3/4 of the total output of the MCMA (Table 6.3). For simplicity and tractability of the analysis, we further aggregate the rest of the industries, because their contribution to the output, as individual sub-sectors is relatively small. The structure of the manufacturing industry has shown a significant shift over time, which is discussed further in the following sections.

6.4 Structural Shift in the Manufacturing Sector in DF, EM and the MCMA

The manufacturing sector in the DF has seen a shift in the share of the manufacturing sub-sectors in the recent past (Figure 6.2). The output data from INEGI (2004) indicates that in the DF, the share of the chemical industry has been growing, at the expense of the metal-products industry. The two sub-sectors, the chemical, and the metal-products, exhibit some interesting dynamics. From 1995 to 2003, the chemical sector saw a significant rise in its share from 31% to 44%, in the total output, whereas the metal-products sector exhibited a downfall in its share from 23% to 10% during the same period. The other two sectors did not show any significant variation in their contribution to the manufacturing sector output. The setting up of new *maquiladoras* or the export-oriented industries in the manufacturing sector on the border region (Gallagher 2004) could be responsible for the shift. One can hypothesize that the increased growth of the metal-products industry in the EM region could be at the expense of deindustrialization of the DF, particularly in the metal-products sector.

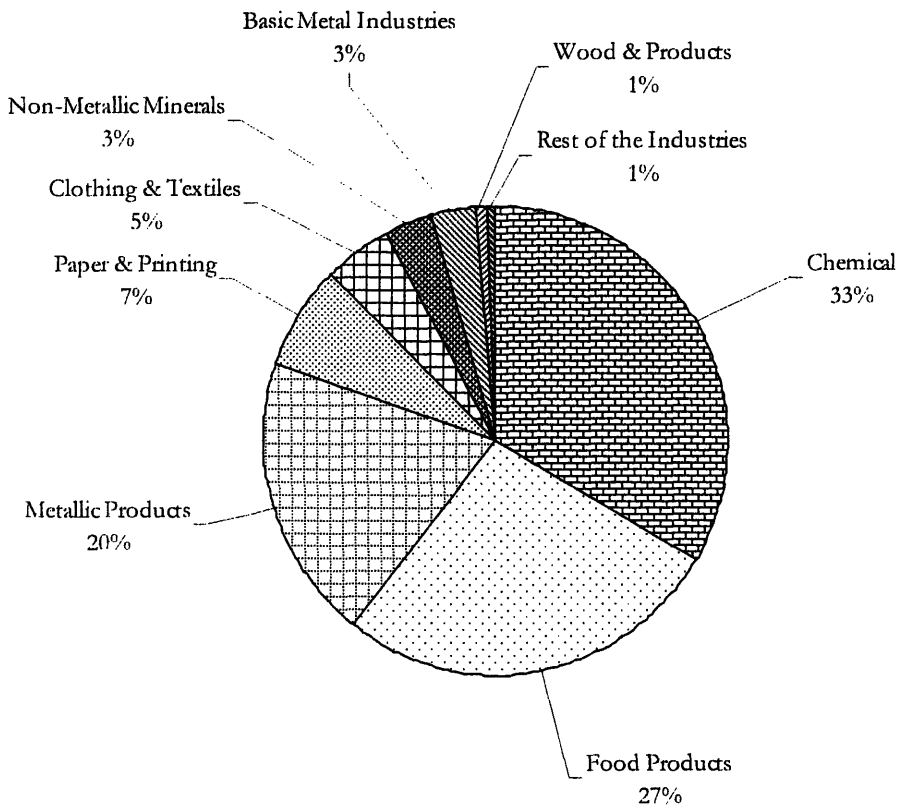
Figure 6.2 Structural Shift in the Manufacturing Sector in the MCMA (1995-2003)



Source: Based on data from INEGI (2004)

The EM is dominated by the metal-products sub-sector, and the chemical sub-sector is a close second. The shift in the structure of the industry indicates that share of different industry sub-sectors in the EM has remained relatively stable. The metal-products industry has shown a small increase in its share in intermediate years, but it has remained constant overall in the period 1995-2003. The share of the metal-products sub-sector increased slightly from 30% in 1995 to 31% in 2003. It is not clear if the intermediate year increase in its share to 36% (in 2000 and 2001) was a result of some fundamental shift or an aberration. We note that the share of the metal-products sub-sector has been on the rise, except in the last two years, i.e., 2002 and 2003. The food and beverage sub-sector also has seen a small increase in its share from 24% in 1995 to 27% in 2003.

Figure 6.3 The Structure of MCMA Manufacturing Sector (2003)



Source: INEGI (2004)

The trend in MCMA is formed by DF and urban municipalities of the EM (37 of the total of 120 municipalities in EM are included in the MCMA). The MCMA structural shift in the industry sub-sectors is shown in Figure 6.2, which indicates a rising trend for the chemical industry, and a declining trend for the metal-products sub-sector. Obviously, the dynamics of the DF the manufacturing industry dominates the sub-sectoral shift in the share of the manufacturing industry output.

Figure 6.3 shows the share of each of the MCMA manufacturing sub-sectors in 2003. It is obvious that currently, the chemical sub-sector, which is also most energy intensive sub-sector, has the highest share in the total industrial output in the MCMA.

Food and beverages, which was at a distant third place in 1995, has increased its share, and is second in total output. At the same time, the metal-product sub-sector has lost its share to these two sub-sectors, which are more energy-intensive.

The share of the chemical sector has increased from 28% in 1995 to 33% in 2003. At the same time, the share of metal-products sector has declined from 26% to 20%. The overall trend has an important role to play in determining the future energy demand of the MCMA and in affecting the air pollution from the consumption of fuels in the valley. We will explore implications of structural change in the manufacturing sector in the following sections. Further, we develop a model to estimate emissions from changes in the structure of industries and other parameters.

The structural shift in the MCMA is depicted in Figure 6.2. After reducing the structure of the MCMA industry into four sub-sectors for the ease of analysis, we note that the share of chemical sub-sector increase by 22% from 1995 to 2003, and the share of metal-products declined by 23.6% in the same duration (Table 6.4). Food and beverages sub-sector also recorded a modest increase in its share during this period, and the cumulative share of all the other sectors declined slightly. The change in share indicated here only tells us relative shift in the output, and in absolute terms it is plausible that the output of a sector declined, whereas its share increased in relative terms, if the total output declines.

Table 6.4 Change in the Structure of MCMA Industrial Sub-sectors (1995-2003)

Industry Sub-sector	Sub-sector Share (fraction)		% Δ in Share
	1995	2003	
Chemical Industry	0.28	0.33	22.2
Metal Products, Machines and Equipment	0.26	0.20	-23.6
Food, Beverages & Tobacco	0.24	0.27	12.3
Others	0.23	0.20	-12.9

Source: Author's calculations based on data from INEGI (2004)

6.5 Energy Intensity of the MCMA Industry

As pointed out in the section above, the manufacturing sector in the MCMA is dominated by the chemical sub-sector, which is an energy intensive sub-sector, compared to the other sub-sectors. Energy intensity of the sub-sectors is given in Table 6.5.

Table 6.5 Energy intensity of MCMA industrial sub-sectors (GJ/1993 mMxP)

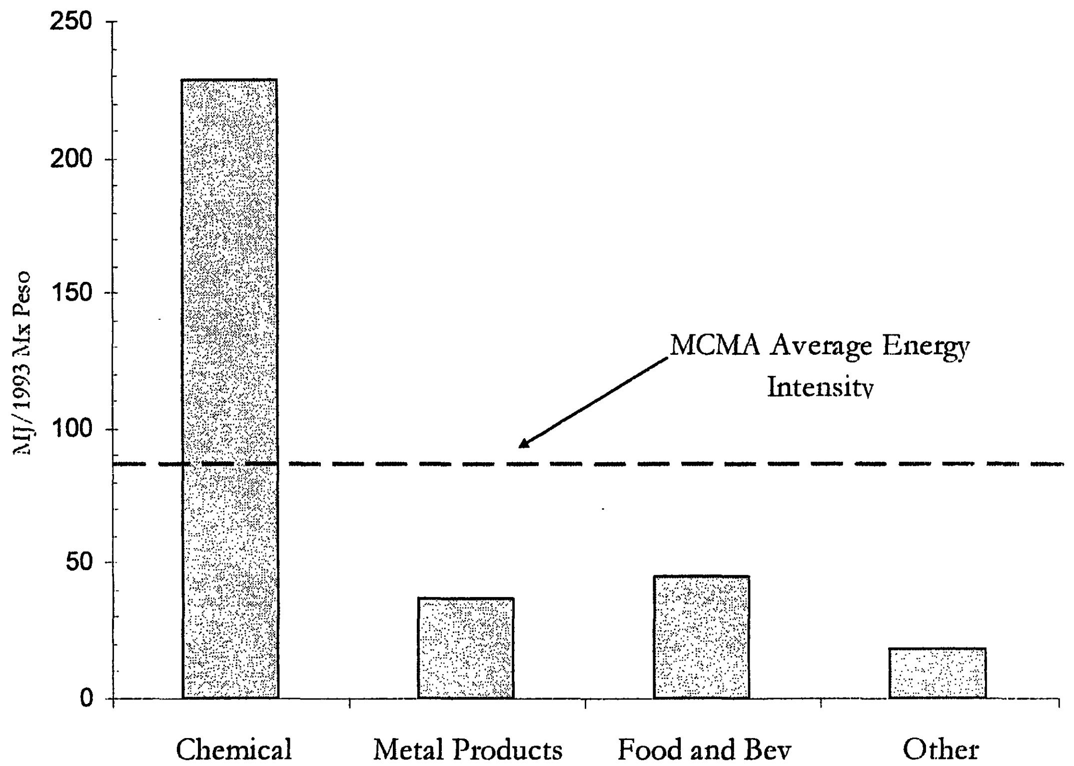
Industry	Energy Intensity
Chemical	221895
Metal Products	35691
Food and Beverages	43765
Others	18249

GJ = Giga(10^9)joule
mMxP = million Mexican Peso
Source: Estimated by the author.

For the four sub-sectors considered for analysis, we estimated energy intensity for the MCMA industry sub-sectors, using the data from the changes in the US, "The Manufacturing Energy Intensity" (EIA 1995), and the "Energy Balance for the MCMA" (Bazan 2000). The energy intensity of chemical sub-sector is six times as much that of metal products sub-sector, and five times as much that of food and beverage sub-sector (Table 6.5).

A comparison of energy intensity of the MCMA industry sub-sectors, compared to the average MCMA industry is shown in Figure 6.4. In the next section, I present results of the MCMA industrial energy-demand estimation for different scenarios taking into account the variation in industrial growth, shift in the industry-mix and energy intensity of the sub-sectors.

Figure 6.4 Energy Intensity of the MCMA Industry Sub-sectors



Source: Author's Estimates

6.6 Industrial Energy Demand Scenarios: Analyzing the Impact of Factors Affecting Industrial Energy Demand

I discussed the industrial energy demand in the MCMA in Section 3.4. Table 3.8 listed the fuel-consumption by industry and other sectors in the MCMA in 1998. For energy demand scenarios, I use 2001 as the base year. In the base year (2001) industrial fuel-energy demand was estimated to be 98.5PJ. In the reference case[5], the MCMA industrial energy demand is estimated to increase to 133PJ in 2025, a 33%

[5] In the reference case, industry structure does not change over the model period, energy intensity of sub-sector continues to decline at a rate of 0.5% per annum, and the growth rate of the MCMA industrial output is low, the one given in the Future Story Divided City (DC).

increase from the base year energy demand. The reference case scenario assumes a business-as-usual (BAU) rate of change in the energy intensity (declining at 0.5% per annum), and the growth of industrial production is assumed to be moderate. I calculate energy demand for scenarios resulting from combinations of different values of the three variables (see Table 6.6), namely growth in industrial output (3 values of annual average industrial growth rates chosen for different Future Stories), change in energy intensity (3 values for changes in the energy intensity), and change in the structure of industry sector (3 different scenarios about structure of the industry-mix). Energy demand in all the resulting 27 (3x3x3) scenarios, changes from baseline energy demand in 2001, and changes from the reference case energy demand in 2025, are given in Table 6.7. The impact of various factors is discussed in details in the following sub-sections.

Table 6.6 The MCMA Energy Demand Scenarios

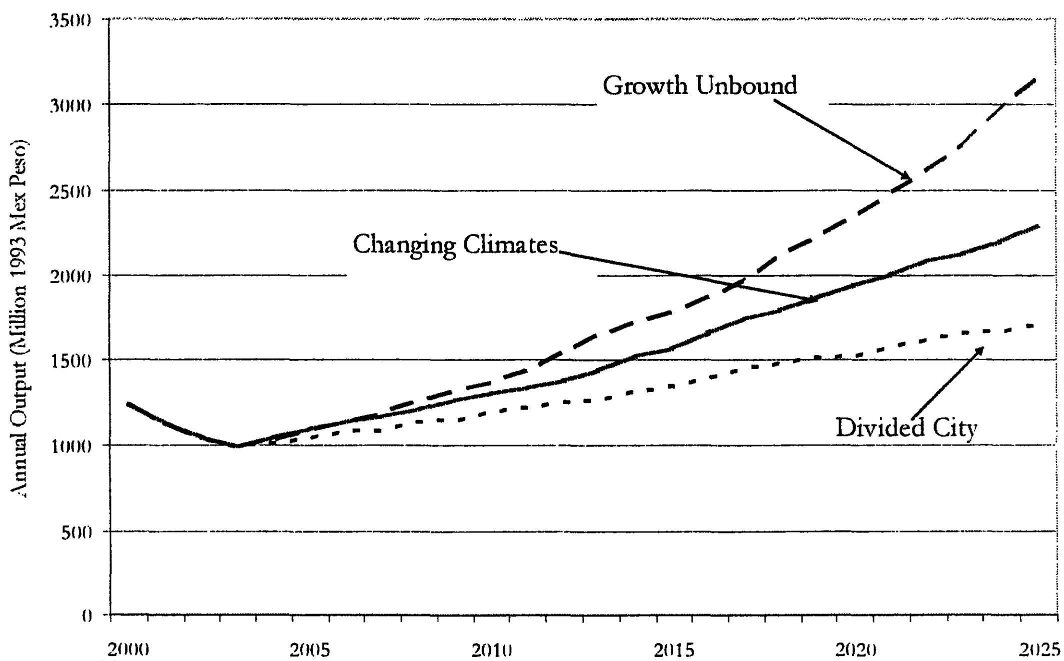
Uncertainty/Option	Code	No.
Uncertainty (Future Stories)		**3**
Divided City	DC	
Changing Climates	CC	
Growth Unbound	GU	
Options (Industrial Structure and Energy Intensity)		
Industrial Structure Options		**3**
Fixed Industry Structure	FIXED	
More Energy-Intensive Industry Structure (Chemical sub-sector dominates)	CHEM	
Less Energy-Intensive Industry Structure (Metal-products sub-sector regains share)	METAL	
Energy Intensity Options		**3**
Slow Energy Intensity Decline Rate	BAU	
Moderate Energy Intensity Decline Rata	MODERATE	
Aggressive Energy Intensity Decline Rate	AGRES	
Total No of Scenarios (Ref. Scenario: DC-FIxed-BAU)		**27**

6.6.1 The Output or Scale Effect

The industrial output from the MCMA in 1993 million Mexican pesos is shown in Figure 6.5. The overall output of the manufacturing sector is governed by the macroeconomic factors in the economy. The output can grow as a result of setting up of additional industrial facilities in the region, or by an increase in the capacity utilization[6] of the existing the manufacturing units.

The three Future Stories (see Chapter 4 for details) capture the increase in output because of macro-level variations in the economy. If we keep the structure of the industry constant at the base year level, and the energy intensity of the industry sub-sectors changes at the business-as-usual pace, we can determine the impact of the change in output on energy consumption in the industry.

Figure 6.5 The MCMA Industrial Sector Output for the Three Future Stories



Source: Dodder et al. 2003

[6] National capacity utilization of the manufacturing industry is reported to be at 70.6 % for the year 1998 (INEGI 2004). We do not have data for the capacity utilization for the MCMA region.

In Table 6.7, if we look at the industrial energy demand corresponding to fixed industrial structure at the base year, and same rate of change of energy intensity (declining at 0.5% per annum), the output effect is manifested in the change in the energy demand by changing the Future Stories. For example, the industrial energy demand in 2025 increases by 35% (177PJ) in Changing Climates, and by 85% in Growth Unbound. If the structure of the industry also changes such that output from the chemical sub-sector increases (chemical sub-sector dominance in the industry-mix), the increase in the energy demand is 70% (Changing Climates), and 135% (Growth Unbound) for the two scenarios. However, if moderate energy-intensity reductions can be implemented, the energy demand is contained to an increase in 17% (Changing Climates) and 63% (Growth Unbound) in the two Future Stories. Thus, the scale effect demonstrates effect of uncertainty on industrial energy demand, resulting from how the future unfolds. We note that the industrial energy demand is slated to increase significantly, even if the structure of industry remains constant, and energy-intensity declines at a slower pace.

6.6.2 The Energy Intensity Effect

Historically, the energy intensity of Mexican industry has shown a modest decline in recent years, to the tune of about 0.5% per annum. We use the IEA energy-intensity data to create different scenarios for energy intensity in the industrial sub-sectors. IEA has reported a rate of decline 3.2% per annum, for the period 1973-1986. In the subsequent years, IEA energy intensity for the manufacturing sector shows a smaller rate of reduction, at 0.5% per annum, which is consistent with the Mexican data. Industry sub-sectors could have very different rates of change in the energy intensity.

However, due to lack of sub-sector specific data, we base our scenarios on these two numbers. For business as usual scenario, we assume 0.5% rate of decrease in energy intensity in the Mexican the manufacturing sector, across all the sub-sectors. The other two scenarios assume a moderate change in energy intensity, at 2% per annum, and an aggressive rate of change of 3% reduction in energy intensity per annum. If the rate of reduction of energy-intensity remains constant at current levels, i.e., 0.5% per year, for 25 years, the energy demand will increase by 33% from the base-year (2001) levels (see Table 6.7). When the moderate energy-intensity reductions are introduced, at the rate of 2% per annum, the energy demand will be contained at 91PJ (an 8% reduction from the current baseline levels). A wide range of scenarios, demonstrating impact of combination of various factors on the MCMA energy demand are shown in the following figures. Figure 6.6 shows output of the chemical sector for the three different Future Stories. The chemical sector output plays an important role in determining the total energy demand, as it is the most energy-intensive of all the sub-sectors in the MCMA industry.

Table 6.7 The MCMA Industrial Energy Demand (2025) and Changes from the Base Year (2001) and Base Case (2025)

Industrial Energy Demand (2001) = 98.5PJ		**Energy Intensity (Annual Rate of Change)**								
		BAU (- 0.5%)			**Moderate (-2%)**			**Aggressive (-3%)**		
Future Story	Industrial Structure	Energy Demand 2025 (PJ)	% Δ Base Year (2001)	% Δ Base Case (2025)	Energy Demand 2025 (PJ)	% Δ Base Year (2001)	% Δ Base Case (2025)	Energy Demand 2025 (PJ)	% Δ Base Year (2001)	% Δ Base Case (2025)
Growth Unbound	Fixed Indus Structure	243	147	85	169	71	28	129	31	-1
	Chemical Dominated	308	213	135	214	117	63	164	67	25
	Metal Prod. Dominated	191	93	45	132	34	0	101	3	-23
Changing Climates	Fixed Indus Structure	177	79	35	121	23	-8	94	-4	-28
	Chemical Dominated	224	127	70	153	56	17	120	21	-9
	Metal Prod. Dominated	138	41	5	95	-4	-28	74	-25	-44
Divided City	Fixed Indus Structure	**131**	33	0	91	-8	-31	70	-29	-47
	Chemical Dominated	166	69	27	115	17	-12	88	-10	-33
	Metal Prod. Dominated	103	5	-22	71	-28	-46	54	-45	-59

Source: Author's calculations (Reference case MCMA industrial fuel-energy demand is given in bold).

The three graphs in Figure 6.6 correspond to the three Future Stories, and each graph shows economic output of the chemical sector for the three scenarios: metal dominated (Metal), fixed industrial structure (Fixed), and chemical dominated (Chem). In the metal dominated scenario, the output of the chemical sector increases by 83%, in business-as-usual (fixed industry structure) the chemical sector output increases by 179%, and in the chemical dominance scenario, the chemical output increases by 294%.

The impact of these scenarios on the MCMA industrial energy demand is shown in Figure 6.7, for the Future Story – Growth Unbound. The three plots correspond to three industry structure options, i.e., fixed industry structure, chemical dominated, and metal-products dominated. Each of the three graphs show estimated industrial energy demand in the MCMA, corresponding to an industrial structure scenario. The three curves on each of the plot correspond to different rates of change of energy intensity: aggressive decline in energy intensity (AGRES), moderate decline in the energy intensity (MODERATE), and business-as-usual rate of change of energy intensity (BAU).

In the GU Future Story (Figure 6.7; Table 6.7), the energy demand in 2025 increases by 3% in the best case scenario, when structure of the industry is metal-dominated, and aggressive energy-intensity reduction (at a rate of 3% per annum) is instituted. If the structure remains the same and the energy-intensity declines at a slower pace, energy demand in 2025 will increase by 147% from the 2001 levels. In the chemical dominated scenario, the energy demand will practically quadruple from the current (2001) levels. This analysis essentially means that in the GU future story, energy demand will not reduce from current levels even if the most dominant options are pursued.

In the Changing Climates scenario, the chemical industry output increases between 33 and 185%, depending upon the structure of the industry. The chemical sector output for this scenario is shown in Figure 6.6.

Yet again, we note that the Future Story variable or the output effect dominates over the structure effect. The best efforts to shift structure of industry from chemical to metal will still result in an increase in the chemical sector output by 33% from the base levels in 2001. The energy demand in Changing Climates scenario increases by 127% if the chemical dominance continues, and decreases by only about 25% if the metal-product sub-sector dominates, while energy-intensity reduces at an aggressive rate. Other than this scenario in most of the other cases the energy demand increases from the base-year level.

For the Future Story – Divided City, in the best possible combination, the chemical sector output remains at the current levels (actually, a 1% reduction), and increases by over 100% in case of chemical sector dominance. The corresponding energy demand scenarios show some reduction. But overall the energy demand growth ranges between -45% and +70% from baseline (Table 6.7).

Most of the scenarios show a substantial increase in the demand of energy by the manufacturing sector because of combination of various factors, output, energy intensity, and structural shift to the energy-intensive industry over the 25 year period. The only exceptions are the scenarios driven by the macroeconomic indicators reflecting low growth in the output (Table 6.7), in Future Story - Divided City.

6.6.3 The Structure or Composition Effect

The relative shares of different sub-sectors represent the structure or the composition of the manufacturing sector. In this research, I analyze three alternative scenarios for the shift in the industry structure. Figure 6.8 shows the impacts of

Figure 6.6 Output of the Chemical Sub-sector for Three Future Stories

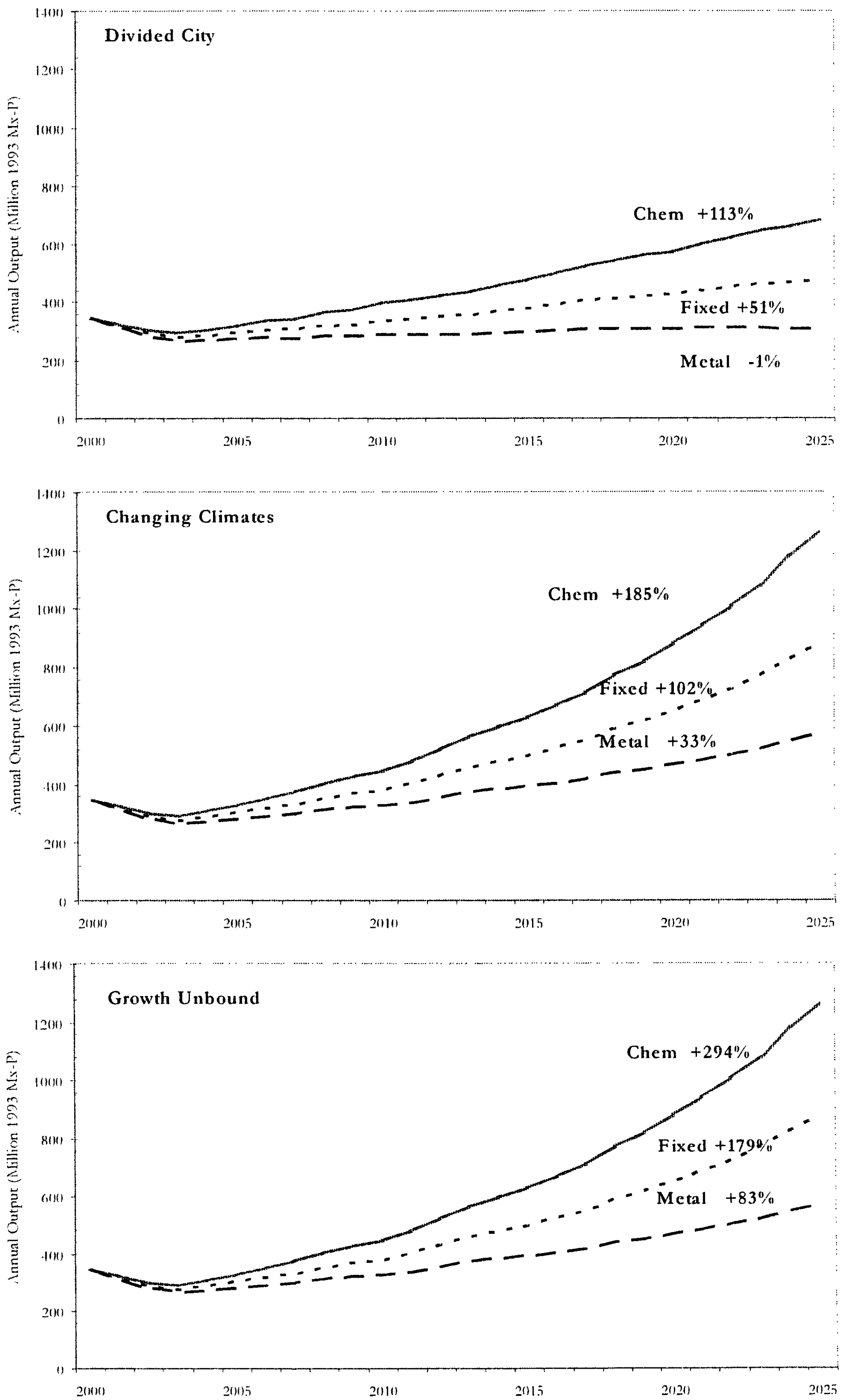
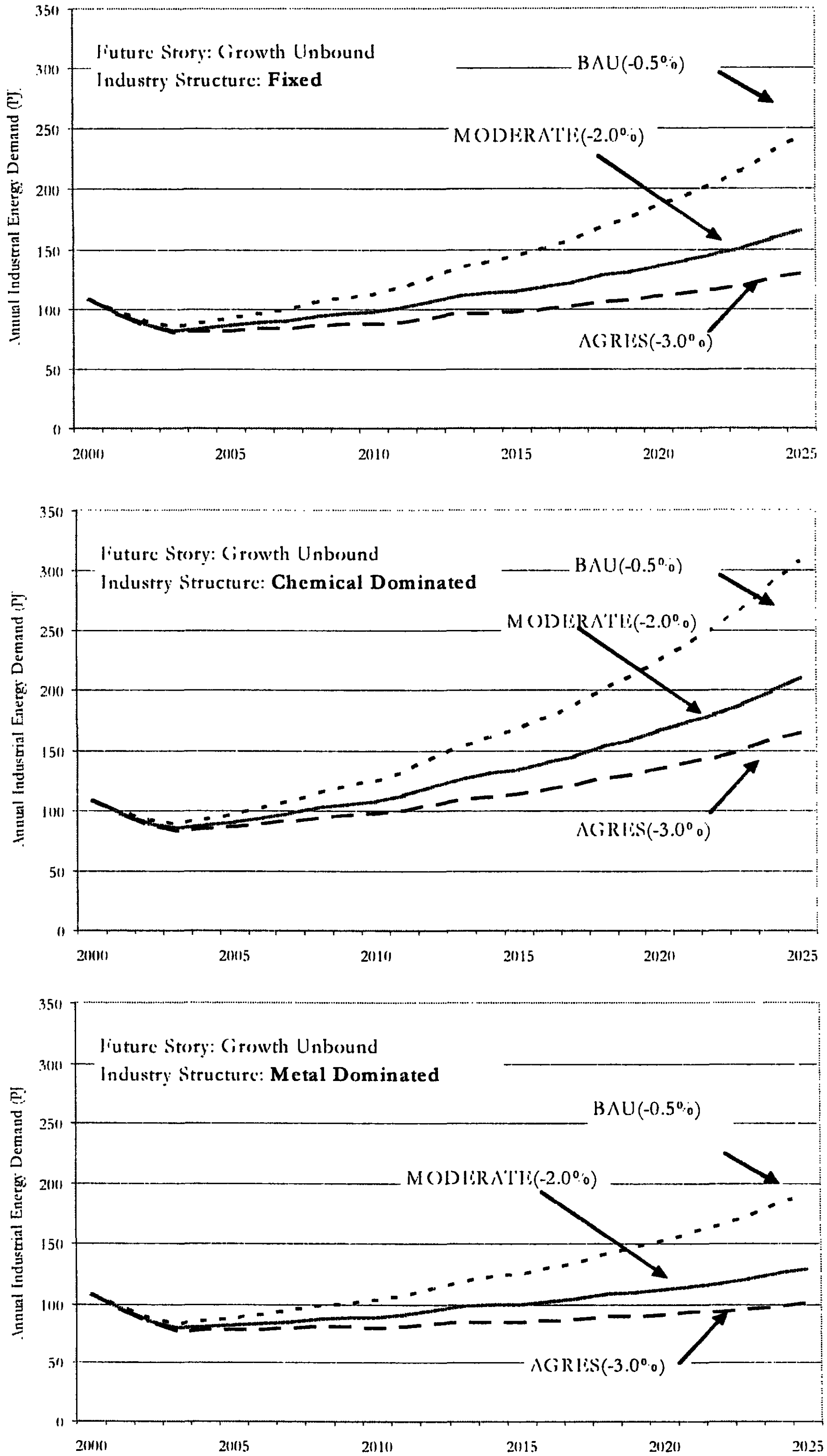


Figure 6.7 Impact of Various Options on Energy Demand (Future Story : Growth Unbound)



changes in the structure (composition effect) and the scale-effect on the energy demand, for Future Story - Growth Unbound.

6.6.3.1 Fixed Industry Structure

The structure of the MCMA manufacturing sector (shown in the Figure 6.3) indicates a dominance of chemical sub-sector, closely followed by the metal products sub-sector. Food & beverages sub-sector is a close third and "other" industry represents sum of the rest of the sub-sectors' shares. In this scenario, we assume that the relative share of output of the total industry sectors remains constant, and every sub-sector grows at the same pace as that of overall industry sector growth. For the fixed industry structure, in the Growth Unbound scenario, the MCMA industrial energy demand increases by 85%, as compared to the base case, and in Changing Climates, it increases by 35% (Table 6.7).

6.6.3.2 Chemical Sub-sector Dominance

The share of chemical industry in the total MCMA industrial output is 28%. This chemical sub-sector dominance scenario assumes that the dominance of chemical sector continues at the expense of metal products industry. In this scenario, the energy consumption implications estimates are based on an increase of share of the chemical sub-sector from 28% to 40% over a period of 25 years, and the increase in share is at the expense of decrease in metal products sub-sector share during the same period. For simplicity, I assume that the other sub-sectors remain constant in their contribution to the economy of the region over the study period.

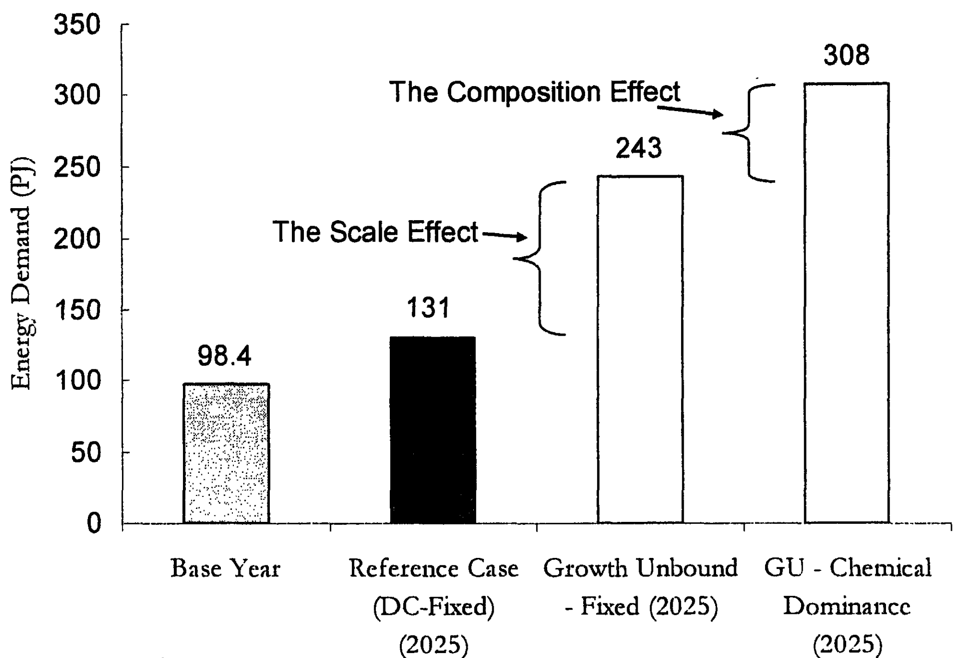
The chemical industry dominance can significantly increase the energy demand as this is the most energy intensive sub-sector in the MCMA. For no change in the energy intensity, the MCMA industrial energy demand in Future Story GU increases by 135%, and in CC, it increases by 70%. The impact of chemical sector dominance is so prominent that in the aggressive energy intensity reduction case, when energy-intensity reductions rate is 3% per annum, the fixed structure energy demand decreases only slightly, by -1%, whereas in chemical dominance scenarios, the energy demand increases by 25%. Meaning that effect of growth and sectoral shift is too prominent for energy-intensity reduction to be able to counter it.

6.6.3.3 The Metal-Products Industry Regaining Share

Although this scenario is less likely to materialize, as the historical data demonstrates a decline in the share of metal products industry over a period of time, at the expense of increase in share of chemical sub-sector. This scenario assumes an increased demand in the metal product industry, mostly driven by the exports. The share of the metal product industry 25% is assumed to increase to 35% linearly during the study period at the expense of chemical industry sub-sector.

In the Future Story DC the energy demand decreases by 22%, if metal industry dominates the industry-mix. In the other two Future Stories, CC and GU, the rate of industrial output growth dwarfs any reductions attainted by changes in the sectoral composition; the energy demand increases to 45% and 5% in GU and CC Future Stories respectively (Table 6.7). For a given output growth rate, if the dominance of chemical industry continues over 25 year period, the energy demand will increase by 53%, and if metal industry regains its share, the energy demand will reduce by about 4 percent.

Figure 6.8 Impact of Structural Shift and Output on the Energy Demand



Source: Author's Estimates

6.7 Policy Implications and Recommendations

Assuming that the output of the industrial sector is solely determined by the supply-demand situation, as governed by the regional, national, and international, macro-economic indicators (see the Future Story formulations in Chapter 4), there are very few policy options that can be pursued to reduce energy demand, and by extension air pollution, from the MCMA manufacturing sector. Modeling of major shifts in the industrial structure, coupled with aggressive reductions in energy-intensity only managed to hold energy demand constant or show reductions in the lowest economic growth scenario (Future Story - Divided City). In the Future Story - Changing Climates, which assumes moderate industrial growth, only two scenarios resulted in holding the energy demand constant, and one scenario demonstrated a reduction in the energy demand. All of the scenarios in the high industrial growth Future Story, Growth Unbound, show significant increase in the energy demand from the base year energy consumption level. Table 6.7 shows consolidated results of various scenarios. In this section, I discuss policy implications and insights from the modeling of the MCMA industrial energy demand scenarios. In the following sub-sections, first, I look at the scenarios in which the energy demand remains constant over the model period. Next, I discuss the scenarios which show a reduction in the energy demand.

6.7.1 Maintaining the Industrial Energy Demand at Current Levels

If the energy demand in year 2025 in any of the scenarios is within +/-5% of the baseline energy demand (2001), I consider that scenario to be able to contain the industrial energy demand in the MCMA at the baseline level.

Only a few scenarios show the MCMA industrial energy demand in 2025 to be within 5% of 2001 level. The scenario DC-Metal (combination of Divided City Future Story, and dominance of metal-products sub-sector) with current energy-intensity reduction rate of 0.5% registers only 5% increase in the industrial energy demand in 2025. In the CC Future Story, moderate energy-intensity reduction (2% per annum) coupled with metal products sub-sector dominance shows a slight reduction in energy demand (4% reduction from the 2001 level). In the same future story, the scenario with aggressive energy-intensity reduction and fixed industrial structure also shows a 4% decline in the industrial energy demand in 2025.

In the GU Future Story, very aggressive energy-intensity reduction rate coupled with the dominance of metal sector is the only scenario in which the energy demand remains within +/-5% of the baseline level.

In the Future Story - Growth Unbound, only one scenario shows energy demand to be contained in the model period. For the Future Story - Changing

Climates, two scenarios maintain base line levels of energy demand in 2025, and in Future Story - Divided City, one scenario shows no change in the MCMA industrial energy demand over the model period. In DC, it is possible to maintain energy demand at the baseline level if structure of the industry shifts from high energy intensity chemical sub-sector to low energy intensity metal products sub-sector. In CC, the dominance of metal-products sub-sector needs to be coupled with moderate reductions in the energy intensity (at 2% per annum) to maintain the base line energy demand. If the structure of the industry remains fixed at the base year level, an aggressive rate of decline in energy intensity (3% per annum) is required to keep the energy demand at the baseline level. And in the GU Future Story, the only combination of changing the industry mix to metal dominated, and achieving aggressive energy-intensity reduction (a 3% decline per annum) can keep the MCMA industrial energy demand from increasing.

6.7.2 Reducing the Energy Demand and Air Pollution

We noted that only a few scenarios were able to contain the energy demand from the MCMA industry at the base year level. Now, let us see if there are any scenarios where we can expect significant reductions in the energy demand, thereby achieving reductions in emissions of air pollutants in the MCMA. Assuming an ad hoc target of reduction of emissions by 50% from the current levels, we need to achieve a 50% reduction in energy demand from the current levels, if everything else remains same.

We note that none of the scenarios (see Table 6.7) show a 50% or greater reduction in the MCMA industrial energy demand. Only the DC Future Story, coupled with dominance of metal-product industry, and aggressive energy-intensity reduction at the rate of 3% per annum, results in a 45% reduction in energy demand. Also, we note that in the GU Future Story significant reductions in the energy demand are impossible, even if we change the structure of industry to low energy-intensity dominated metal-products sub-sector and aim for aggressive energy-intensity reduction goal of 3% per annum decline. In the Changing Climates Future Story, aggressive energy-intensity reductions and structural changes to increase the share of metal-products result in 25% reduction in energy demand in 2025 from the baseline level.

In the DC scenario, we note that the energy demand reduction is possible in 5 out of total 9 scenarios (Table 6.7). This means that the growth in the energy demand is essentially driven by exogenous factors, such as the macroeconomic drivers of growth. Policies to reduce energy demand by reducing energy intensity, and influencing structure of the industry can only succeed in containing and reducing emissions if they are also able to reduce output from the industries, i.e., change in the economic structure of the MCMA takes place in such a way that the manufacturing activity in the MCMA is reduced and substituted by the service sector.

6.8 Summary and Conclusions

From the several scenarios analyzed in the previous sections, it is clear that in determining the energy demand in the long run, the exogenous variable (growth rate of industrial output) is the most important. Even after the structural shift to reduce energy intensity by influencing the industry-mix is implemented, in most of the scenarios, the energy demand increases from the base year (2001). Only when the industrial growth rate is low (in the Divided City - Future Story), we see moderate reductions in the industrial energy demand in some of the scenarios. None of the scenarios show a significant decline in the energy demand in 2025 to meet the ad hoc air-pollution abatement goal of reducing industrial emissions by 50%.

This finding has important implications for policy design. It is clear that the options to reduce energy intensity and change the structure of the industry by influencing the industry-mix alone are unable to tame the energy demand, and thereby the air pollution. Also, these scenarios do not take into account political and economic feasibility of implementing the aggressive reductions in the energy intensity (3% decline per annum) or bringing about drastic changes in the industry-mix in the MCMA.

However, we have not yet modeled the technology options, such as end-of-pipe controls, and fuel-switching. In the next chapter, I model the technology and policy options which aim to reduce emissions by implementing fuel-switching, deploying end-of-pipe or process controls, and influencing the output from the industrial sector. I also estimate the capital cost and policy cost of these options to conduct a multi-attribute tradeoff analysis to identify the most cost-effective options.

Chapter 7

Identifying Robust Strategies: A Multi-attribute Tradeoff Analysis

In the previous chapter, I estimated the MCMA industrial energy demand under several scenarios. Specifically, I modeled the impact of following three factors on the energy demand: changes in the industrial output as a result of changing macroeconomic environment depicted by the three Future Stories, structural shift in the MCMA industry, and changes in the energy intensity of sub-sectors. I concluded that because of dominance of exogenous variable, the industrial output, options to reduce industrial energy demand in the MCMA by changing the structure from high energy intensive industry to low energy intensive industry, and by accelerating the rate of energy-intensity decline, were not enough to achieve sustained and substantial reductions. In this chapter, I introduce additional technology and policy options -- fuel-switching, end-of-pipe and process controls, such as NO_x and PM control equipment, and deindustrialization -- and model their impacts on emissions from the industrial sources in the MCMA. Further, I estimate the cost of technology and policy options and conduct a multi-attribute tradeoff analysis to identify cost-effective sets of options to reduce the industrial air pollution in the MCMA.

In this chapter, I use the model developed in Chapter 5 to estimate industrial emissions in the MCMA. Section 7.1 lays out the framework for naming convention of various scenarios developed in this research. Section 7.2 discusses modeling of the industrial growth and output, and lays out the components of the policy cost of influencing the growth rate of output from the manufacturing sector in the MCMA. In the previous chapter, I modeled changes in the structure of the industry energy intensity to estimate industrial energy demand. In Section 7.3, I introduce a variable Structure Adjusted Energy Intensity (SAEI) which integrates the impacts of structural shift and sub-sectoral energy intensity into the model to estimate emissions of air pollutants. In Sections 7.4, I discuss fuel-switching and its implication on emissions. Section 7.5 deals with the target pollutants and their control technologies. In Section 7.6 and 7.7, I model control technology penetration for NO_x and PM, and their costs. Section 7.8 discusses the cost-modeling of energy-efficiency improvements, and capital-stock turnover. In Section 7.9, I present results of the modeling and conduct a scenario analysis. The tradeoff analysis is the topic of discussion in Section 7.10, and results and conclusions are presented in Section 7.11.

7.1 Scenario Nomenclature

A scenario is composed of uncertainty and a combination of options or a strategy. The uncertainty in estimating emissions from industrial sources arises from our inability to predict the future path of macroeconomic growth of the MCMA. It is captured by the three Future Stories; Divided City (DC), Changing Climates (CC), and Growth Unbound (GU). A typical scenario name is DC-CUNULELI. The first two letters, DC, refer to the Future Story, Divided City. This could be CC for Changing Climates and GU for Growth Unbound. The first two letters after the hyphen, CU here, indicate the deindustrialization policy to influence the output from the industrial sector in the MCMA. A **cu**rrent level of manufacturing output is represented by the scenario code CU, whereas MO (for **mo**derate) refers to small policy induced influence on the rate of industrial output growth. A substantial **re**duction in output is referred by scenario key RE.

Next letter in the scenario name, N, refers to **n**o change in the Structure Adjusted Energy Intensity (SAEI) of the industrial sector. A value M for this variable indicates a **m**oderate rate of decrease in the SAEI. **S**ubstantial rate of structure-adjusted energy-intensity reduction is indicated by letter S.

Next letter of the scenario, U, refers to current level of clean fuel fraction, moderate rate of fuel-switching is indicated by O. An aggressive rate of fuel-switching is shown by letter A in the scenario name. Next letter, L, indicates low level of end-of-pipe (EOP) controls saturation for NO_x. Medium and high levels of EOP control saturation are indicated by M and H respectively. Table 7.1 lists the technology and policy options, and provides a guide to the naming convention of scenarios used in this research.

Table 7.1 Technology and Policy Options

Uncertainty/Option	Code	No.
Uncertainty (Future Stories)		**3**
Divided City	DC	
Changing Climates	CC	
Growth Unbound	GU	
Policy Options (Industrial Output, SAEI and Fuel Switching)		
Industrial Output Options		**3**
Current Level of Output	**CU**	
Moderate Reduction in Output	MO	
Substantial Reduction in Output	RE	
Structure Adjusted Energy Intensity Options		**3**
No Change in SAEI	**N**	
Moderate Reduction in SAEI	M	
Substantial Reduction in SAEI	S	
Fuel Switching Options		**3**
Current Level of CFF	**U**	
Slow Fuel Switching	O	
Fast Fuel Switching	A	
Technology Options (EOP and Process Controls)		
Emission Controls – NO_x		**3**
Low Penetration of ECS	**L**	
Moderate Penetration of ECS	M	
High Penetration of ECS	H	
Operation and Maintenance (NO_x Control)		**1**
Decrease in NO_x Control Efficiency	**E**	
Emission Controls – PM		**3**
Low Penetration of ECS	**L**	
Moderate Penetration of ECS	M	
High Penetration of ECS	H	
Operation and Maintenance (PM Control)		**1**
Existing Control Efficiency	**I**	
Ref. Strategy: CUNULELI	Strategies	**243**
Ref. Scenario: DC-CUNULELI	Scenarios	**729**

The next letter **E** refers to maintenance of control equipment, and its impact on emissions. However, to keep the analysis tractable and scenarios manageable, this research assumes value of this variable to be constant throughout the scenarios. The next letter **L** also indicates penetration of EOP controls – for PM. The last letter in the scenario **I** indicate a the control efficiency (often a function of operation and maintenance) of PM controls. Letter **E** refers to reduced efficiency of control over the study period, whereas letter **I** assume the control efficiency to remain constant throughout the study period.

7.2 Deindustrialization and its Impact on the Industrial Output

The most important macroeconomic variable affecting emissions growth is the industrial production or output. Output of the industrial sector is treated as an exogenous variable, which changes with the macroeconomic indicators reflected by the three Future Stories (see Chapter 4 for details). The growth rate of the MCMA industrial sector, as given by the Future Stories, determines the gross output from the industrial sector. Figure 7.1 depicts the gross industrial output for the MCMA for the three Future Stories, in absence of any targeted policy initiative to influence industrial production. The annual average industrial-economic growth rates for the three Future Stories are 1.3%, 2.5% and 3.8% per annum for Divided City, Changing Climates and Growth Unbound respectively. This growth rate in the industrial output, *ceteris paribus*, would result in an increase of 38% (DC), 85% (CC) and 155% (GU) increase in all the pollutant emissions from the industrial sector from 2001 to 2025. A policy to reduce the growth in output, by promoting deindustrialization or encouraging setting up of new manufacturing facilities outside of the valley would help reduce the growth of emissions in the valley. To model the impact of any policy to affect the level of output growth, I define a variable, activity level, α, which assumes the values shown in the Table 7.2. If the autonomous annual growth rate of industrial output for a given Future Story, for a given year, t, is β, then the industrial output for year (t+1) is given as:

$$\mathbf{IO_{t+1} = IO_t * [1 + (\beta/100) * (1 - \alpha/100)],} \quad \mathbf{(7.1)}$$

where,

IO_{t+1} is the Industrial Output in the year t+1 ($)

IO_t is the industrial output in the year t ($)

β is the exogenous growth rate as determined by the respective Future Story (% per year)

α refers to the policy induced reduction in the industrial output (% per year). Policy induced industrial growth rates are calculated in Table 7.3, and resulting change in the industrial output from 2001 to 2025, is shown in Table 7.4.

Table 7.2 Values of the Policy Parameter (α) Affecting Exogenous Growth Rate of Industrial Output (%)

Future Story	Exogenous Growth Rate (β)	Current Output (CU)	Moderate Decline (MO)	Reduced Output (RE)
	(%)	Parameter Value (α) (%)		
Divided City	1.3	0	40	80
Changing Climates	2.5	0	50	100
Growth Unbound	3.8	0	30	60

Table 7.3 Policy Induced Industrial Output Growth Rate (%)

Future Story	Exogenous Growth Rate (β)	Current Output (CU)	Moderate Decline (MO)	Reduced Output (RE)
	(%)	Policy Induced Growth Rate (%)		
Divided City	1.30	1.30	0.78	0.26
Changing Climates	2.50	2.50	1.25	0.00
Growth Unbound	3.80	3.80	2.66	1.52

Source: Calculated on basis of Table 7.2 and Equation (7.1)

The three levels of policy initiated values of output growth rates are affected by the variable α, which assumes different values in the three Future Stories. CU refers to the **current** level of activity, where, the policy does not affect the autonomous growth rate of industrial output in any of the three Future Stories. In the **mod**erate (MO) deindustrialization policy, the autonomous growth rate is reduced by 40, 50 and 30% in the three Future Stories, DC, CC and GU respectively. In an aggressive policy implementation (RE), the growth rate is significantly reduced. In Changing Climates, the autonomous growth rate (β) is nullified by the policy initiative, which means the output from the industries will remain constant throughout the model period. In the other two scenarios Divided City and Growth Unbound, the exogenous growth rate is reduced by 80, and 60% respectively.

In the GU Future Story, since the economic growth is the key factor, the value of variable α has been selected such that the output growth rate is curtailed by 30% and 60% levels, from the no-policy growth rate. For example, if the growth rate in the no-policy case were 5% per annum, the growth rate in the MO scenario will be 5*(1-30/100) = 3.5% per annum (see Table 7.3), and in the RE case, the growth rate would be, 2% per annum. In the CC Future Story, the environmental consciousness is more and it should be possible to introduce a more aggressive policy, as reflected in the values of options selected for the variable in this scenario, i.e., 50% and 100% for MO and RE option. If the exogenous growth rate for Changing Climates in a given year was 5%, the model growth rate would be half of that when moderate output reduction (MO) policy option is introduced, and it will be 0% when RE policy option is introduced. In the DC scenario, since the industrial and economic outlook is not so bright, it many not be possible to introduce aggressive output reduction policy options. Therefore, the values chosen for policy variable are lower than that in the scenario CC, and higher than that in the scenario GU.

Implications for industrial economic growth due to deindustrialization policy are given in Table 7.4. If deindustrialization is included as a policy, the change in the industrial economic output in 2025 could directly affect the emissions, if all other remains constant. I have chosen only one option where the industrial economic output is frozen at the base year (2001) level, through out the study period. This freezing of industrial output at the base year level in the Changing Climates Future

Story, when combined with very aggressive technology and policy options, leads to some dramatic, albeit unrealistic, reductions in the emissions (see Table 7.12).

Table 7.4 Percent Change in Industrial Economic Output (from 2001 to 2025)

Future Story	Exogenous Growth (2001-2025)	Policy Induced Industrial Economic Growth (2001-2025)		
Option/Policy	No Policy	**Current** Output (CU)	**Moderate** Decline (MO)	**Reduced** Output (RE)
Divided City	38	38	21	7
Changing Climates	85	85	36	0
Growth Unbound	154	154	93	46

Source: Calculated on basis of Table 7.3

7.2.1 The Cost of Deindustrialization

Estimating the cost of deindustrialization is a complex issue. An input-output framework (see Miller and Blair 1985) can help identify the primary and secondary impacts of the reduction in industrial economic output, by estimating the value of the intermediate goods and services, and by quantification of the employment impacts. However, an input-output framework for the MCMA is not available at this time; therefore, I have neglected secondary and tertiary impacts of reduction in the industrial output. The primary impact of the de-industrialization policy would be reflected in the reduced regional output from the industrial sector in the MCMA. We have estimated the lost manufacturing production or output in monetary terms to analyze impact of the de-industrialization policy on emissions. The value of lost output is given by –

$$\mathbf{LO_{t+1} = IO_t *(1+ \beta) - IO_{t+1}} \qquad \mathbf{(7.2)}$$

Where,

LO_{t+1} = Policy induced reduction in industrial output ($)

IO_t = Actual Industrial output in year t ($)

β = the autonomous industrial growth rate for year t, for a given Future Story
IO_{t+1} = Actual industrial output in year t+1, given by Equation 7.1.

Figure 7.1 shows the industrial output for the three Future Stories, and Figure 7.2 shows the foregone production or lost industrial output, due to the deindustrialization policy, for the three Future Stories, and two options. Moderate reduction in policy-induced output is shown by MO, and significant reduction in policy-induced output is given by RE. Initial rise in the lost output (up to 2003) represents the observed actual decline in the output. The industrial economic output in Figure 7.1 is calculated using the cumulative average growth rates for the three Future Stories.

Figure 7.1Industrial Economic Output (2001-2025) (billion Pesos)

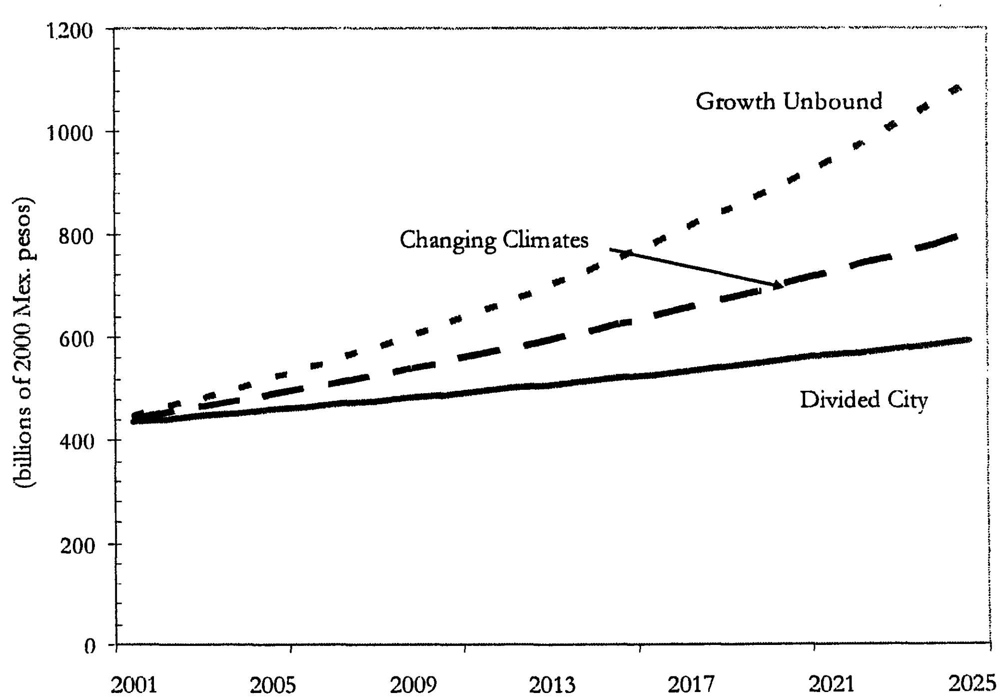
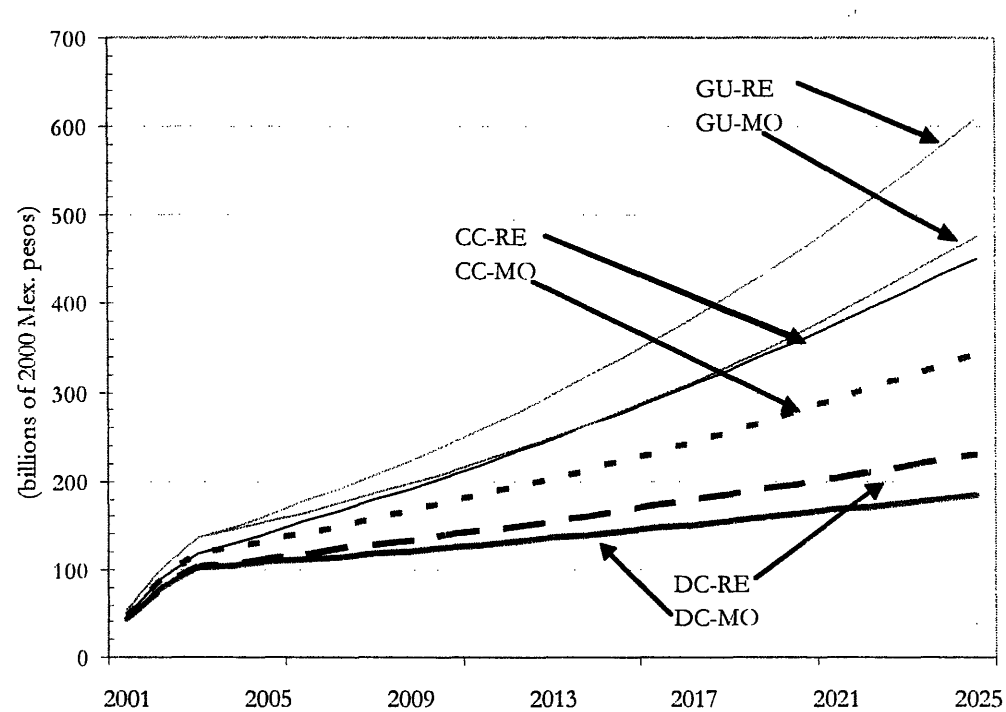


Figure 7.2 Forgone Industrial Economic Output (2001-2025) (billion Pesos)



7.3 The Structure Adjusted Energy Intensity

Chapter 6, explored implications of the shift in the industrial structure of the MCMA, and changes in the energy intensity, on energy demand, separately. In this chapter, I have integrated the two options in a variable, structure adjusted energy intensity (SAEI). The appropriate values for SAEI have been chosen on the basis of the analysis done in the previous chapter. The three dominant industries in the MCMA, chemical, metal products, and food & beverages, make up about three-quarters of the total industrial output in the MCMA. Of the three sub-sectors, chemical is the most energy intensive, and has shown an increase in its share in the recent past. I demonstrate that if the trend continues, an increase in the structure adjusted energy intensity could result in significant increase in the energy demand and therefore air pollutant emissions (see Chapter 6 for details of the analysis). A reduction in the energy intensity is possible by implementing energy efficiency measures, and by investment in renewing the capital stock. The cost of improving energy efficiency and reducing energy intensity is estimated and modeled. Details of cost-modeling of the energy-intensity focused investment are given in section 7.6. The values of the SAEI used for modeling emissions from various scenarios are shown in Table 7.5.

Table 7.5 Structure Adjusted Energy Intensity (Percent Annual Reduction)

Option / Future Story	No or Small Change in SAEI (N)	Moderate Reduction in SAEI (M)	Significant Reduction in SAEI (S)
Divided City	0.50	0.65	0.90
Changing Climates	1.00	2.00	3.80
Growth Unbound	0.75	1.50	3.00

Source: Estimates based on energy demand scenarios (Chapter 6).

The SAEI values were estimated from different industrial energy demand scenarios discussed in Chapter 6. The annual average rate of decline of SAEI varies from 0.5% to 3.8%, and the values selected for the three options N, M and S, for three Future Stories, are in this range. In Future Story, CC, the values of SAEI chosen show a more aggressive approach to reducing energy intensity and shifting the structure of the MCMA manufacturing sector toward less energy intensive production since in this Future Story the society would be more amenable to such an aggressive strategy to reduce emissions. However, the capital investment required to achieve an equivalent level of reduction in the energy intensity in the DC Future Story will likely not be available; therefore, a slower rate of decline in SAEI is chosen for that option. For the GU, the rate of decline in SAEI is higher than that in the DC Future Story, as fast economic growth means economic constraints will be less likely to affect energy-intensity reduction efforts.

7.4 Fuel Switching

Rate of fuel switching can have significant impact on the emissions of certain pollutants. The MCMA has witnessed serious efforts to reduce consumption of high-sulfur liquid fuels, by introducing natural gas. According to the energy balance for the MCMA (Bazan 2000), in 1998, the industrial sector consumed 78% of its primary fuels in the form of gaseous fuels (thus a Clean Fuel Fraction, CFF = 0.78). Remaining 22% of the primary energy demand was met by the industrial diesel. Switching from diesel to natural gas at an accelerated pace can reduce emissions of local air pollutants, and that of greenhouse gases as well. Particularly, the SO_x emissions are directly related to the sulfur content of the fuel, and particulate matter emission factors are also higher for the liquid fuels as compared to natural gas. The Clean Fuel Fraction (CFF), which is a ratio of the energy consumed in gaseous form (i.e., natural gas or LPG) to the total primary energy consumed by the manufacturing sector is used to model fuel-switching. A higher CFF indicates a higher share of clean-burning fuel, and a low value of CFF represents an increased share of liquid fuel, industrial diesel. Different saturation values of CFF are assumed corresponding to different Future Stories (see Table 7.6). The high saturation of CFF in the Changing Climates Future Story indicates a change in the preferences of consumers, resulting in higher penetration of clean burning gaseous fuels. The saturation value of CFF in the end of year 2025 is highest, 0.95, in the Future Story - Changing Climate. The saturation of clean fuels is not assumed to be 100% in any of the scenarios, to account for the fact that some industrial applications continue to rely on liquid fuels for their operation.

Table 7.6 Values of Clean Fuel Fraction Used to Model Emissions (Fraction)

Option / Future Story	Current Fuel-mix (U)	Moderate Fuel-switch (O)	Aggressive Fuel-switch (A)
Divided City	0.73	0.75	0.78
Changing Climates	0.80	0.85	0.95
Growth Unbound	0.78	0.82	0.86

Source: Bazan (2000); Author's estimate.

The reduction in the current clean fuel fraction (CFF) from 0.78 to 0.73 is assumed in the DC scenario. Although it is legally banned to bring in and burn high-sulfur fuel-oil in the MCMA, in the recent past, there is anecdotal evidence (Sanchez 2003) about illegal importing of high-sulfur fuel-oil into the MCMA. In the DC scenario, if the scarcity of the economic resources to meet the energy demand continues, reduction in the CFF is a possibility, which is reflected by the downward change in CFF in the DC Future Story.

In Changing Climates, natural gas is likely to be meeting the majority of the industrial energy demands, reflected by high values of the CFF. However, the saturation level of CFF can not be higher than 95%, as certain industrial applications will continue to use some amount of liquid fuel. The change in the CFF is modeled in such a way that it increases from the base value to the saturation level in equal incremental steps over the study period.

7.5 Target Pollutants and Control Options

I have modeled and analyzed emissions of three criteria pollutants -- NO_x, PM_{10} and SO_2 -- from industrial sources in the MCMA. Emissions of hydrocarbons and carbon monoxide have not been estimated for the following reasons. More than 99% of carbon monoxide emissions are emitted by mobile sources, particularly automobiles. In addition to mobile sources, the commercial and informal sector is a dominant source of the hydrocarbon emissions in the MCMA. The share of industrial sources in hydrocarbon emissions is very small (see Chapter 3 for details).

7.5.1 NO_x Reduction Options

NO_x emissions from the industry primarily result from combustion of fossil fuels to generate process heat (Beer 2000; Schnelle and Brown 2002). As discussed earlier (see Chapter 5) NO_x emissions are primarily a function of combustion temperature. I have modeled two categories of policy options that specifically target NO_x emissions. Both of these are technology options. First, combustion modification, in which the configuration of the combustion chamber is altered in such a way that combustion takes place at a lower temperatures, thereby generating lower levels of thermal NO_x. Combustion modifications can result in significant reduction of NO_x emissions, on the order of 30-50% in a cost-effective way. There are several ways to achieve this. One is flue-gas-recirculation, and another is staged combustion. The other category of technology options is installation of end-of-pipe control options. Two popular sub-categories in the end-of-pipe controls are selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR). Both of these control technologies are more expensive than the combustion modification technologies. However, the control efficiency of these technologies can be as high as 90%. Fuel-switching also affects NO_x emissions. However, fuel-switching has not been treated as a categorical option to reduce NO_x emissions from industrial sources in the MCMA, but the impact of fuel-switching on NO_x emissions is taken into account. A list of NO_x control options and their technical description can be found in NESCAUM (2000), and STAPPA & ALAPCO (1994).

7.5.2 PM_{10} Control Options

PM_{10} emissions from the industrial sources can be combustion-related, and process-emissions. For the MCMA, the data from cedula de operación (COA) indicate that the split is approximately 50-50 between these two sources. The process emissions are dependent on the characteristics of the process and activity level, whereas the combustion-related PM_{10} emissions are dependent on quality and quantity of the fuel burnt, and the type and configuration of combustion equipment. Particularly, for the liquid fuels, such as fuel-oil, sulfur content plays a key role in determining primary (and secondary) PM_{10} emissions. The technology options included in this chapter for the PM_{10} control are fuel-switching, change in the fuel-quality (low-sulfur fuel-oil) and end-of-pipe controls, such as bag-house filters, or cyclone filters. Electrostatic precipitators are popular control equipment, commonly used in the power plants burning coal, however, due to high capital and operation cost; it is not a control technology of choice for industries. Emission controls for PM are cheaper, and have higher efficiency (on the order of 99% reduction by weight) than the NO_x controls.

7.5.3 SO_x Reduction Options

Emissions of SO_x from the MCMA industry come primarily as fugitive emissions from industrial processes in the Chemical industry, and from combustion of fossil-fuels containing sulfur. The process emissions can be arrested by specially designed equipment. The combustion-generated sulfur dioxide emissions can be reduced by changing the fuel from liquid to gaseous fuels, or by reducing the sulfur content in the liquid fuels. There are end-of-pipe controls, such as flue-gas-desulfurization (FGD) or scrubbers, very commonly used in the power plants using high-sulfur coal. However, they are too expensive to be considered for installation in industrial facilities in the MCMA. In this research end-of-pipe SO_x controls are not modeled; SO_x emissions are only affected by fuel-switching from liquid to gaseous fuels, and by the change in the value of the industrial output affecting fuel consumption. In the past, the MCMA industry sector has used heavy fuel-oil with a very high (up to 4%) sulfur content leading to high SO_x emissions. However, the fuel-oil has been replaced by the low-sulfur industrial-diesel in the MCMA (Favela 2000). The effect of this change is obvious. The SO_x concentrations have been reported in the valley to be lower than the ambient standards.

7.6 Modeling End-of-pipe and Process Control Populations

Measures, such as improving energy efficiency, reducing energy intensity, and fuel-switching, present a limited set of options to reduce emissions. End-of-pipe (EOP) controls can help achieve significant reductions of targeted pollutant emissions. To model NO_x and PM EOP control equipment penetrations, we used a log-log model to estimate saturation, with appropriate parameters. The saturation values for NO_x and PM were chosen to indicate higher level of PM saturation as opposed to lower saturation of the NO_x controls, as evidence suggests that there are already some PM controls installed in the industrial sector in the MCMA (COA 2001). Moreover, cost of NO_x control installation is much higher than that of EOP controls for PM. We assumed a 50% control efficiency for the NO_x control equipment, and 98% efficiency for the PM control equipment (NESCAUM 2001; STAPPA & ALAPCO 1996).

The 2025 saturation levels (in percent) for NO_x and PM control technology options are shown in Table 7.7 and Table 7.8 respectively. The number of NO_x and PM controls modeled is shown in the following Figure.

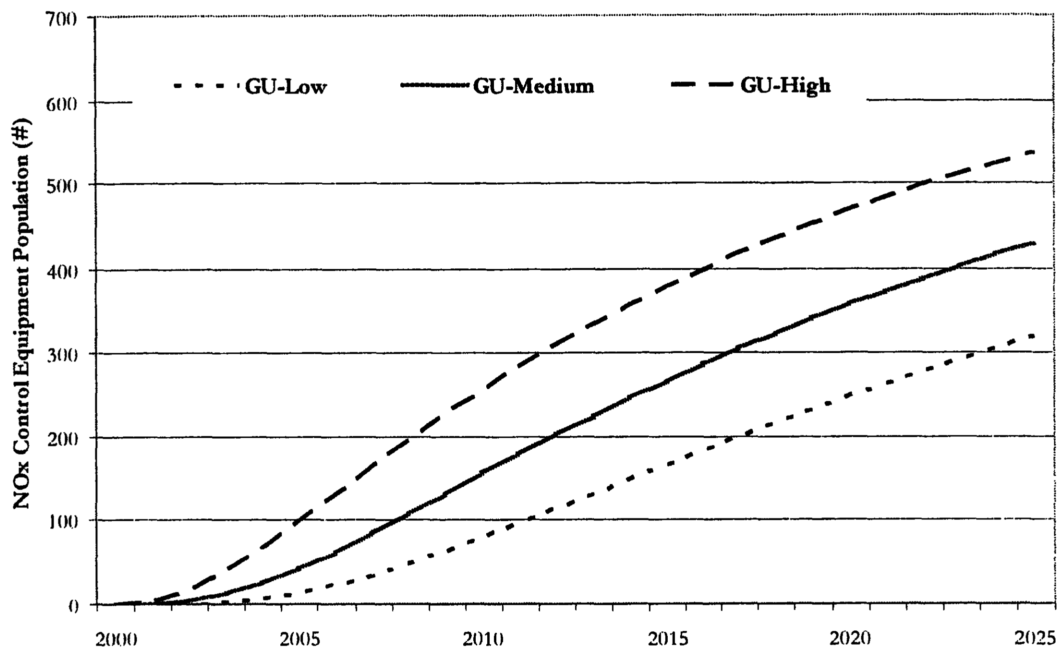
Table 7.7 Penetration of NO_x Controls in the MCMA in 2025 (%)

	Saturation Levels (%) in 2025		
Option / Future Story	Low (L)	Medium (M)	High (H)
Divided City	10	15	20
Changing Climates	20	25	30
Growth Unbound	15	20	25

Source: Author's estimate.

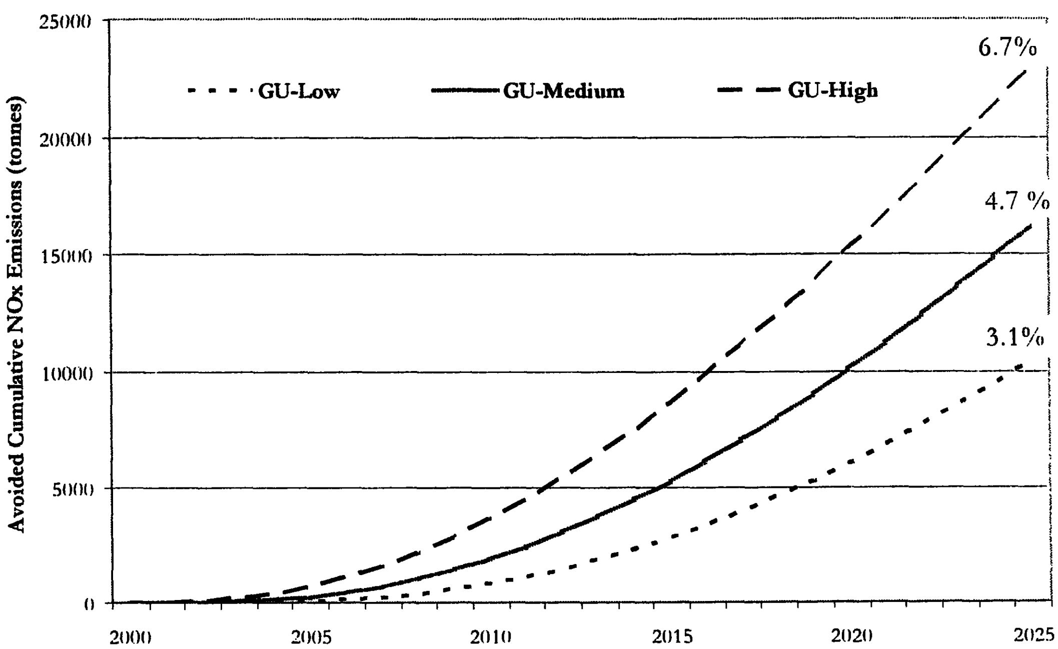
The saturation level of NO_x controls in the Future Story – Growth Unbound, results in the following cumulative avoided emissions of NO_x from the industrial sources (see Figure 7.4). The cumulative avoided emissions are estimated on basis of a uniform emissions distribution among the polluter population. For the GU Future Story, the three options result in cumulative emission reduction of 3.1% for low penetration of NO_x controls to 6.7% for the highest penetration of modeled NO_x controls. A comparative estimate of the net present value of the control cost for installation of PM and NO_x controls is given in Figure 7.7. Note that the cumulative avoided emissions for NO_x are less than that for PM_{10}, and their cost is much higher than the PM controls. The PM control saturation in the MCMA is assumed higher, resulting in more PM controls as compared to the NO_x controls. The EOP PM Controls

Figure 7.3 Number of NO_x Control Installations in the MCMA (Future Story – Growth Unbound)



Source: Author's estimates.

Figure 7.4 Estimated Cumulative Avoided Emissions of NO_x



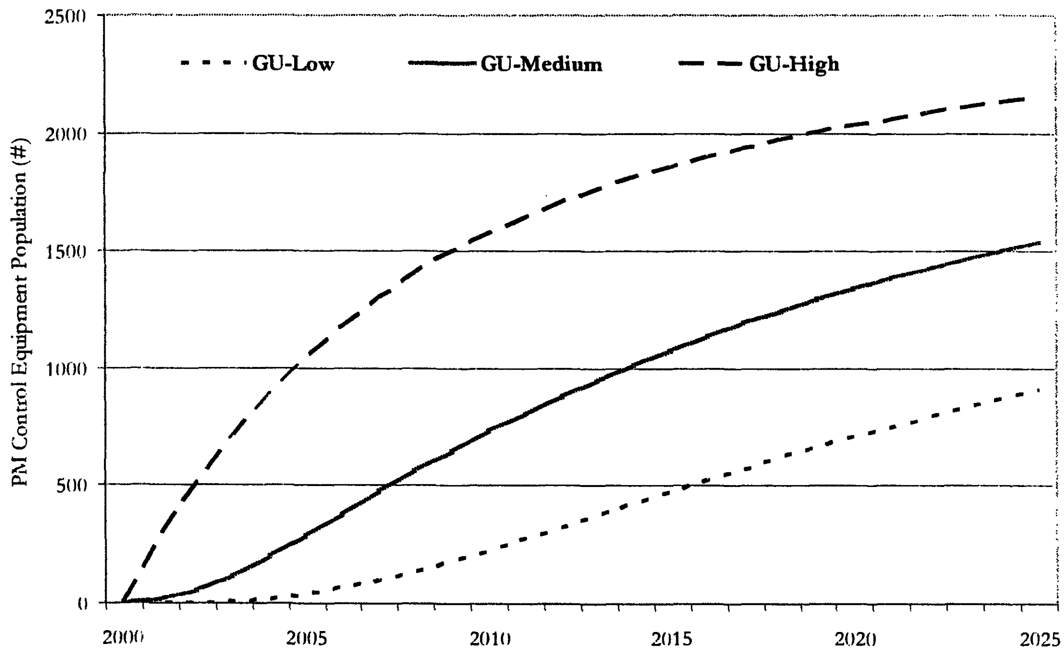
saturation modeled is listed in the following Table, and number of PM controls modeled during 2000-2025 is shown in Figure 7.5.

Table 7.8 PM Control Penetration in 2025 the MCMA industry (%)

	Saturation Levels (%) in 2025		
Option Future Story	Low (L)	Medium (M)	High (H)
Divided City	20	30	40
Changing Climates	30	40	50
Growth Unbound	25	35	45

Source: Author's estimate.

Figure 7.5 Number of PM Controls installations in the MCMA (Future Story – Growth Unbound)



In the scenario CC-High (see Figure 7.1 and 7.2), i.e., for Future Story CC, when the control option indicates a high penetration of the control technologies, the installation of PM and NO_x control in the initial period is high as the long term emissions reduction benefit accrue every year from early installation, leading to a larger cumulative reduction in NO_x, and PM emissions. The cumulative net present cost of PM EOP installations is much lower than that of NO_x controls (Figure 7.7) due to higher capital cost of the NO_x controls.

Figure 7.6 The Cumulative Avoided Emissions of PM_{10}

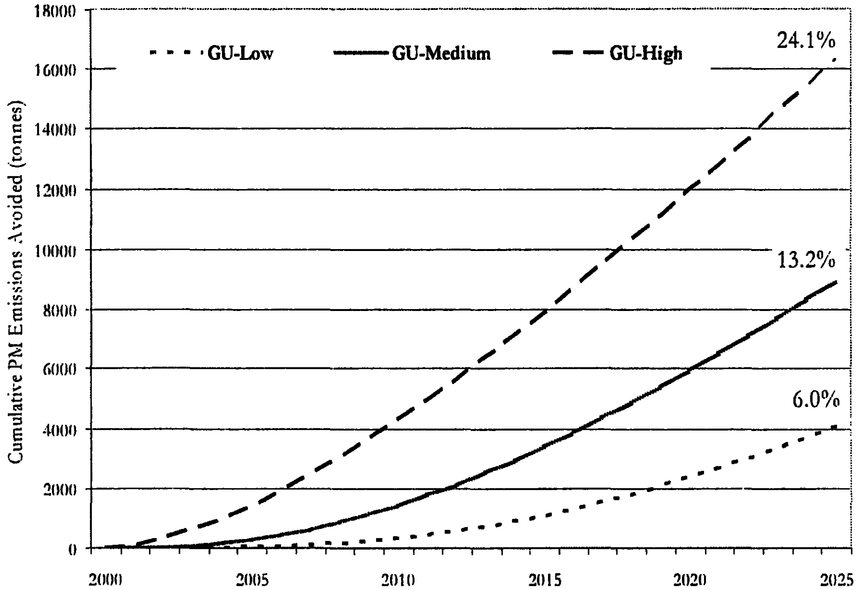
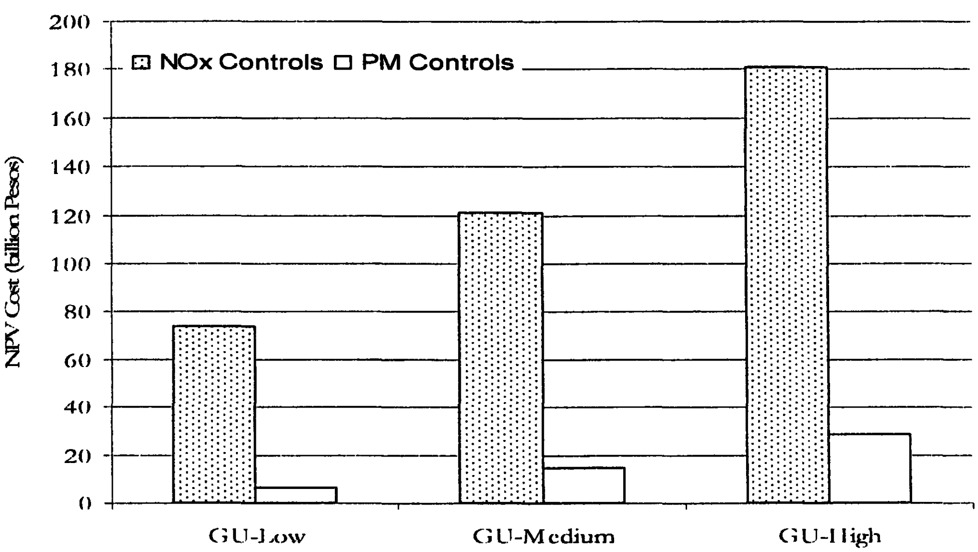


Figure 7.7 The Net Present Value of NO_x and PM Control Costs



7.7 Cost Modeling of Control Technologies

The following direct and indirect cost attributes have been used to model total direct cost, and total policy cost: capital cost, operation and maintenance cost, air quality program implementation cost, and cost of foregone production. Table 7.9 indicates the cost components included in direct cost and total policy cost. Since no data for air quality implementation plan was available, a fixed percentage of the capital cost was attributed to the air quality program implementation cost.

Table 7.9 The Cost Attributes for Technology and Policy Options

Cost Components	Capital	O&M	AQP	Forgone Output
Direct Cost	x	x	x	
Policy Cost	x	x	x	x

O&M = Operation and Maintenance
AQP = Air Quality Program

Cost of the control technologies is included to estimate net present value of the total cost of options and strategies over the study period (2000-2025). The way capital cost and operation and maintenance cost is modeled is explained hereunder.

7.7.1 Capital Cost

The total capital investment in a given year is the sum of the capital costs for end-of-pipe (EOP) NO_x or PM control installations in that year. The capital recovery factor, multiplied by the total capital investment gives the actual capital outlay by any industry. It indicates the cost of borrowing capital for investment in the EOP control technology. The actual cost of EOP control depends on a lot of factors, such as size of the plant, size of combustion equipment, level of initial pollutant emissions, etc. In the macro-level modeling, that this study undertakes, it is impossible to take into account all these factors. Therefore, in modeling the capital cost, we have included cost of an average value for a NO_x control and PM control equipment, which have 50% and 98% control efficiency respectively. It is noteworthy that NO_x control equipment can have a very high cost for higher efficiency levels. Particularly, the cost of consumables, such as that of ammonia, or that of the catalyst -- in case of a selective catalytic reduction – can be very high, and may affect overall cost effectiveness. The NO_x control equipment, the capital cost and operation & maintenance cost used in this study is for a medium size process heat boiler based on NESCAUM (2000) case study for Chevron process heater boiler. The PM Control-cost and operation & maintenance cost is based on STAPPA & ALAPCO (1996) case study for oil based industrial boiler.

Capital Cost_NOx (t) = CRF*NO_NOx (t)*Cost_NOx (7.3)

Where,

CRF = capital recovery factor, indicates the cost of borrowing money

NO_NOx(t) = Number of NO_x controls installed in a given year t

Cost_NOx = Unit Capital Cost of NO_x Control Equipment,

Similarly, the capital cost for PM controls are estimated and included in the model.

7.7.2 Operation and Maintenance Cost

The operation and maintenance cost can be significant for EOP control technologies; therefore, it is essential to include them in the total cost estimations. If not maintained properly, the efficacy of the EOP controls can drop significantly. In a given year, to estimate total operation and maintenance cost, we need to sum all the installed EOP controls and multiply the same with annual average operation and maintenance cost.

Table 7.10 Capital and O&M Costs of NO_x and PM Controls Modeled

	Capital Cost (2000 US$)	O & M Cost (2000 US$)	Control Efficiency
NO_x Control[1]	1500000	41000	50%
PM Control[2]	350000	124000	98%

Source: 1. NESCAUM (2000)
2. STAPPA and ALAPCO (1996)

So, in a given year t, the total operation and maintenance cost will be given as hereunder –

Total_ NOx _O&M (t) = Annual_Nox_O&M *(Σ NO_NOx(t))

Total_PM_O&M (t) = Annual_PM_O&M *(Σ NO_PM(t))

Total_O&M (t) = Total_Nox_O&M(t) + Total_PM_O&M (t) **(7.4)**

where,

Total_O&M(t) is total operation and maintenance cost in year t.

Annual_PM_O&M (t) is annual operation and maintenance cost for PM control ($)

Annual_NOx_O&M (t) is annual operation and maintenance cost for one NO_x control installation ($)

NO_NOx (t) is number of EOP NOx controls installed in year t.

NO_PM(t) is number of EOP PM controls installed in year t.

7.8 Cost Modeling of Energy Efficiency Improvements

Industry continuously keeps including new equipment and machines to its capital stock. New equipment is often more energy efficient than the old equipment. In theory, we should expect to see a negative relationship between capital investment and energy intensity, i.e., with increased capital investment, we should see a decrease in the energy intensity. So, for modeling the impact of overall capital expenditures, we need to have a quantitative relationship between the level of investment and the resulting improvement in energy intensity. Or from a policy perspective one can ask, how much capital investment would it take to reduce a given level of energy consumption? Unfortunately, literature does not provide any simple answer to this question.

7.8.1 Capital Expenditure and Reduction in Energy Intensity

The hypothesis that increased expenditure on capital would result in installation of newer and more energy efficient equipment and machinery; thereby, reducing the overall energy intensity does not find very strong support in the literature. For example, Miketa (2001) has analyzed the energy-intensity development in the manufacturing sector in the developing and developed countries. Miketa's model captures impact of three variables – investment, output, and energy prices – on the change in energy intensity. For non-metallic products industry, the results indicate a negative coefficient, but statistically insignificant. In seven out of the ten industries considered, Miketa finds positive coefficients. Negative coefficient are found only in three industries, with only one industry showing statistically significant correlation between increase in capital expenditure and decrease in energy intensity. One possible explanation for this could be that the result of all investment does not necessarily result in reduced energy intensity. Kumar (2003) finds that research and development expenditures contribute to a decline in firm-level energy intensity. But Worrell (2001) concludes that the use of economic measures is not good enough to understand changes in energy intensity.

One tends to agree with the conclusion of Miketa (2001) that not all investments have the effect of reducing the energy intensity. However, this does not exclude possibility of targeted investment, with a focus on reducing energy intensity. Moreover, continued innovation in the processes and technology should be able to translate in improved processes and reduced energy intensity (De Beer 1998).

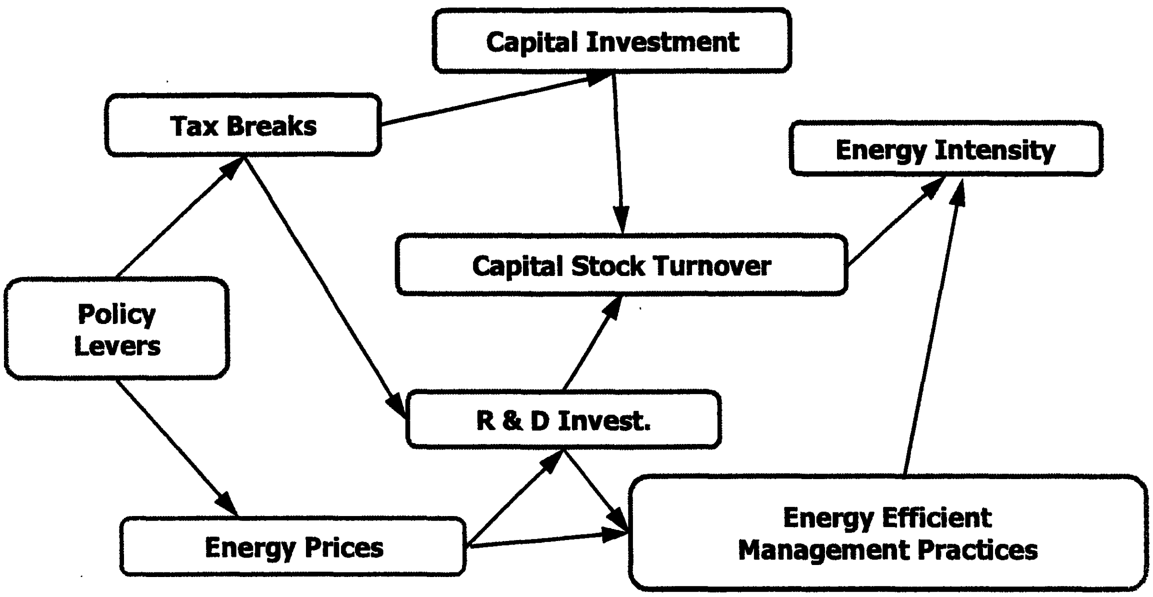
In the MCMA, the industry sector added new equipment worth 9 billion pesos in 1998 (INEGI 1999). The capital expenditure for addition of new equipment was 9% of the total fixed assets used for production, and a small fraction (only 2.2%) of total industrial production on a value added basis.

Capital stock turn-over is one mechanism by which energy intensity of the industry increases (Figure 7.8). Another mechanism to improve productivity and efficiency of the equipment is by modifying or retrofitting existing equipment. Jacoby and Wing (1999) have emphasized the importance of both of the processes, stock turnover and retrofit, in understanding the dynamics of energy efficiency of the industry. Worrell and Biermans (Forthcoming) have noted the need to understand the role of both these processes in improving energy efficiency. They found that for the US steel industry, annual average improvement in the specific electricity consumption was 1.3% per annum, over a twelve year period (1990-2002). Of the total improvement in the energy efficiency, 0.7% was attributed to the stock turnover and 0.5% was attributed to the retrofit of stock in service.

For the purpose data-analysis in this chapter, we do not differentiate between the processes leading to energy efficiency, and treat stock-turnover, and retrofit together. As the census data available to us do not differentiate between capital expenditure for "retrofitting" and for "stock turnover". However, we realize that in the long run this differentiation may be important from a policy perspective, and should be taken into account. If the marginal rate of energy efficiency improvement for retrofitting is higher than that of stock turnover, it may be worthwhile to pursue that policy. In Mexico, there are regional[1] differences in the rate of industrial capital stock turnover.

[1] We note that rate of addition to the capital stock is higher in Mexico, than that in the MCMA. Moreover, the fraction spent nationwide on new equipment and machines for production is 3% of the total output. Presumably, the rate of addition of new equipment is higher in the newly developing industrial areas, such as the export oriented industries in the north of the country on the US-Mexico border region.

Figure 7.8 Capital Stock Turn Over and Energy Intensity



7.8.2 Engineering and Economics Approach

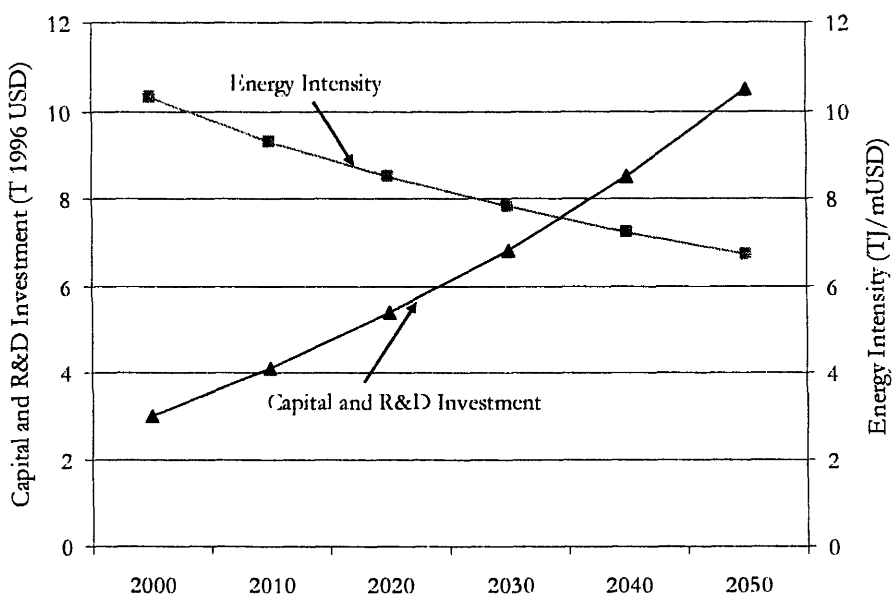
Within a given industrial sector, there are significant differences in the way machinery and equipment are used and capital investment decisions are made. Moreover the nature of the process of stock turnover, and retrofit is not well understood (Worrell, Forthcoming), and there are no reasonable empirical relations available. Lempert et al. (2002) contends that differences in the industrial processes used by different plants make it difficult to understand the relationship between capital cycles and changes to energy efficiency. Due to inability of an economic approach to provide us with a reasonable model that captures the impact of capital investment on energy efficiency, we turn to the engineering-economic analysis of specific technologies, to achieve energy-intensity reductions. However, the known energy-intensity estimates are specific to one industry (steel production industry, in this particular case) and the model and results are only valid for a small segment of industry, so its generalization may not be valid.

7.8.3 Aggregate Economic Approach

Models estimating the impact of policies on the economy resulting from global climate change often use a top-down approach to incorporate parameters such as technical change and capital investment, research and development etc (see Jacoby and Wing 1999; Wing 2001).

Wing (2001) has included the role of induced technical change in computable general equilibrium models for climate-change policy for the United States. He uses a computable general equilibrium model of the US economy to numerically estimate the impact of price-induced technical change on emissions of greenhouse gases. Although he does not specifically investigate the role of the investment and research and development on changes in energy intensity, the reference scenario for the US economy indicates a correlation between the investment and energy intensity, as shown in Figure 7.9.

Figure 7.9 Capital and R & D investment and energy intensity in the US economy (2000-2050)



Source: Based on Wing (2001)

Figure 7.9 demonstrates anticipated changes in investment in R&D and improvements in energy intensity over a 50 year period for the US economy. On average, a 5% increment in the capital and R&D investment is related to about 0.69% decrease in the energy intensity. We can use this data to estimate incremental capital investments in the MCMA to attain a given change in the energy intensity. The investment intensity (ratio of investment in a given year to the total capital stock) of the MCMA economy and that of the US is very similar. For the US economy, the capital and R&D investment in a given year is ranges from 9.5 to 11% of the capital stock (Wing 2001), whereas for the MCMA, this value was 9% in 1998 (INEGI 1999). Therefore, although the structure of the US and Mexican economies are different, it is justified to use the US specific data for our estimations, in the wake of no other source of Mexican specific pertinent information being available.

7.8.4 Energy Prices and Energy Intensity

The energy crises in the 1970s indicated that the energy demand is price-elastic in the long-term, whereas in the short-term the energy demand is price inelastic. In the three Future Stories, the energy prices are expected to change. Mostashari (2002) has modeled and selected the fuel-quality and prices for the Mexican economy for the period 2000-2025 for each of the three Future Stories. Although an increase in energy prices decreases energy demand in the long-run, the mechanism by which prices affect long-run energy demand is, through inducing technical change, by way of promoting investment in the energy saving technologies, modernizing of the manufacturing processes and turning over of the capital stock. In this thesis, induced impact of energy prices on energy efficiency is not taken into account, as the model estimations of fuel price changes are relatively small, and for a short-term (25 years).

7.9 The MCMA Industrial Emissions Scenarios

Implementation of various technology and policy options result in different emission profiles for the industrial sector. I crafted several scenarios[2] (see Table 7.1) by taking into account various combinations of possible variations in the key parameters affecting emissions from the industrial sources in the MCMA. Each technology and policy option has some associated cost to the society. I estimated the cost of implementation of a given policy by calculating the net present value of the total cost over the model period (2000-2025), using the discounted cash flow (DCF) method. Cumulative emissions over the model period, and net present value of the cost were then used as the basis for evaluation of a particular strategy[2] (a combination of technology and policy options).

7.9.1 The Reference Scenario (DC-CUNULELI)

The reference scenario assumes that industry output attains a cumulative average growth rate of 1.3% per annum (corresponding to the Future Story – Divided City), and there are no policy induced reductions in the activity (CU). The SAEI reduces at the historical rate of 0.5% per annum, and there is no targeted effort to reduce energy intensity (N). The clean fuel fraction remains 0.78 throughout the study period (2000-2025) (U), and penetration of NO_x controls is low (L) and the control efficiency decreases over the study period (E). The PM control equipment penetration is also low (L), but the control efficiency remains constant during the study period (I). Thus the reference strategy is CUNULELI, and when combined with the reference Future Story (DC), we get the reference scenario DC-CUNULELI. The dip in the emission in the initial years represents the actual decline resulting from

[2] Each strategy is a unique combination of technology and policy options. For example, CUNULELI is name of a strategy. A scenario is a strategy when it also includes the "uncertainty". In this research, a strategy means a combination of technology and policy options, and a scenario means how that strategy plays out under uncertainty. The three Future Stories represent the uncertainty. CUNULELI is a strategy, whereas DC-CUNULELI is a scenario.

reduced output from the MCMA industry sector due to the recent economic downturn.

The reference scenarios indicate substantial increases in the emissions during 2001-2025. For the Future Story - Divided City, annual emissions of NO_x are likely to increase by 42% in 2025 from their current low levels (2003), and PM_{10} emissions will rise by 35% during the same period. The fuel-energy demand will increase by 54% during this period. The final energy demand by the MCMA industrial sector during this period is shown in Figure 7.10. The energy demand will increase from current 126PJ, in 2003 to 193PJ in 2025. Reference case emissions and percent change in 2025 emissions from 2001 is listed in Table 7.11.

For the Future Story – Changing Climates, we note that the energy demand increases more than that in the Divided City, but emissions do not increase in the same proportion. Particularly, PM_{10} emissions trajectory shows a decline in emissions in 2025 in this Future Story as compared to Divided City.

Table 7.11 Reference Case (CUNULELI) Emissions of NO_x and PM_{10}

	PM_{10} Emissions (kt)			NO_x Emissions (kt)		
Future Story	2001	2025	% Δ	2001	2025	% Δ
Divided City	1.95	1.96	0.82	16.55	18.83	13.83
Changing Climates	1.95	1.78	-8.41	16.55	19.62	18.58
Growth Unbound	1.95	3.66	88.03	16.55	38.15	130.59

Energy demand trajectory for reference scenario in the Future Story – Growth Unbound indicates that the energy demand, in absence of any aggressive energy-intensity measures, skyrocket to over 300PJ. Emissions trajectory of the target pollutants NO_x and PM_{10} is shown in Figure 7.11 for the reference strategy for three Future Stories – Growth Unbound. The significant rise in the emissions in this scenario demonstrates that how future unfolds, will play a significant role in determining the emissions trajectory from the MCMA industrial sources.

Figure 7.10 Industrial Energy Demand in the Reference Case (CUNULELI) for the Three Future Stories

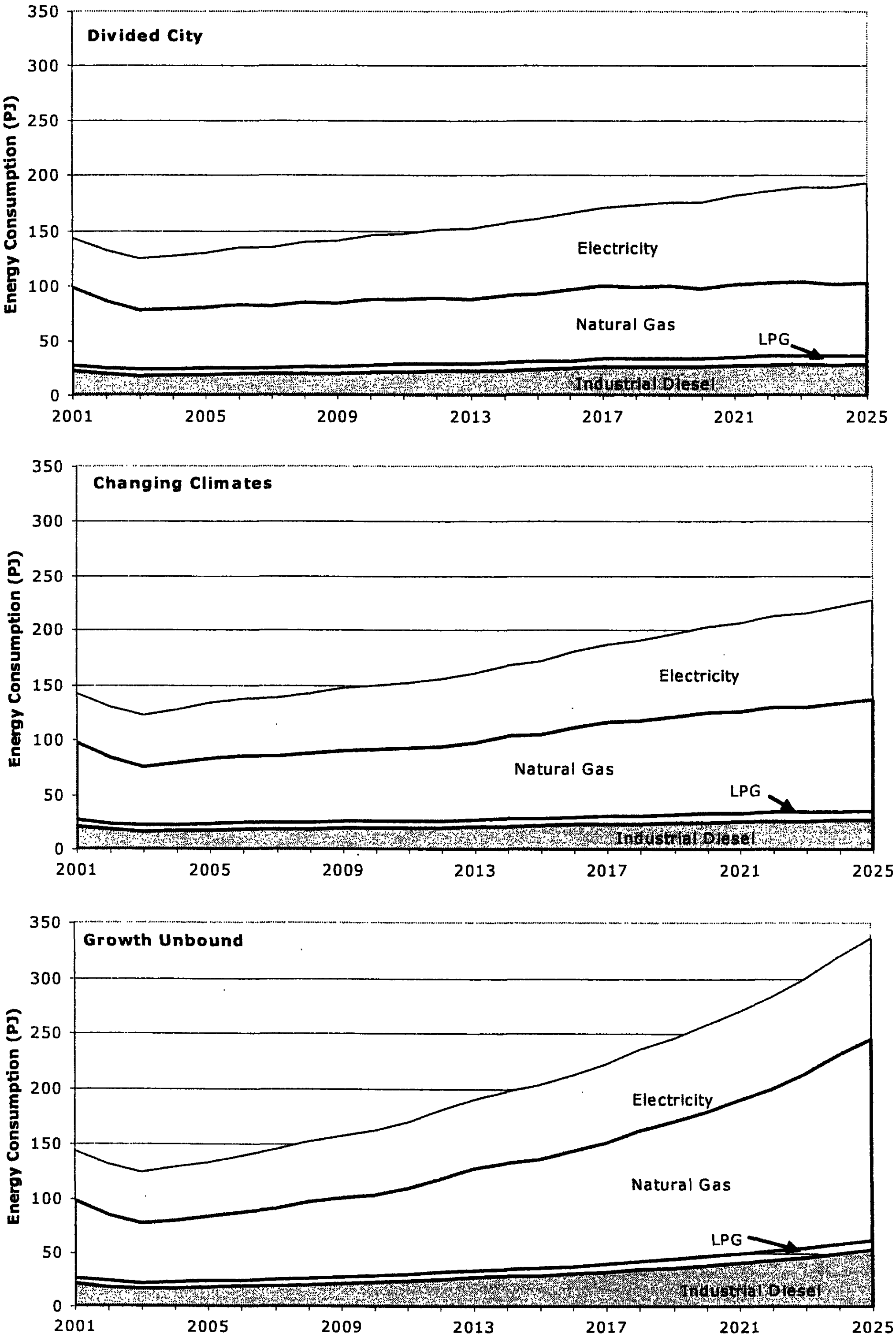
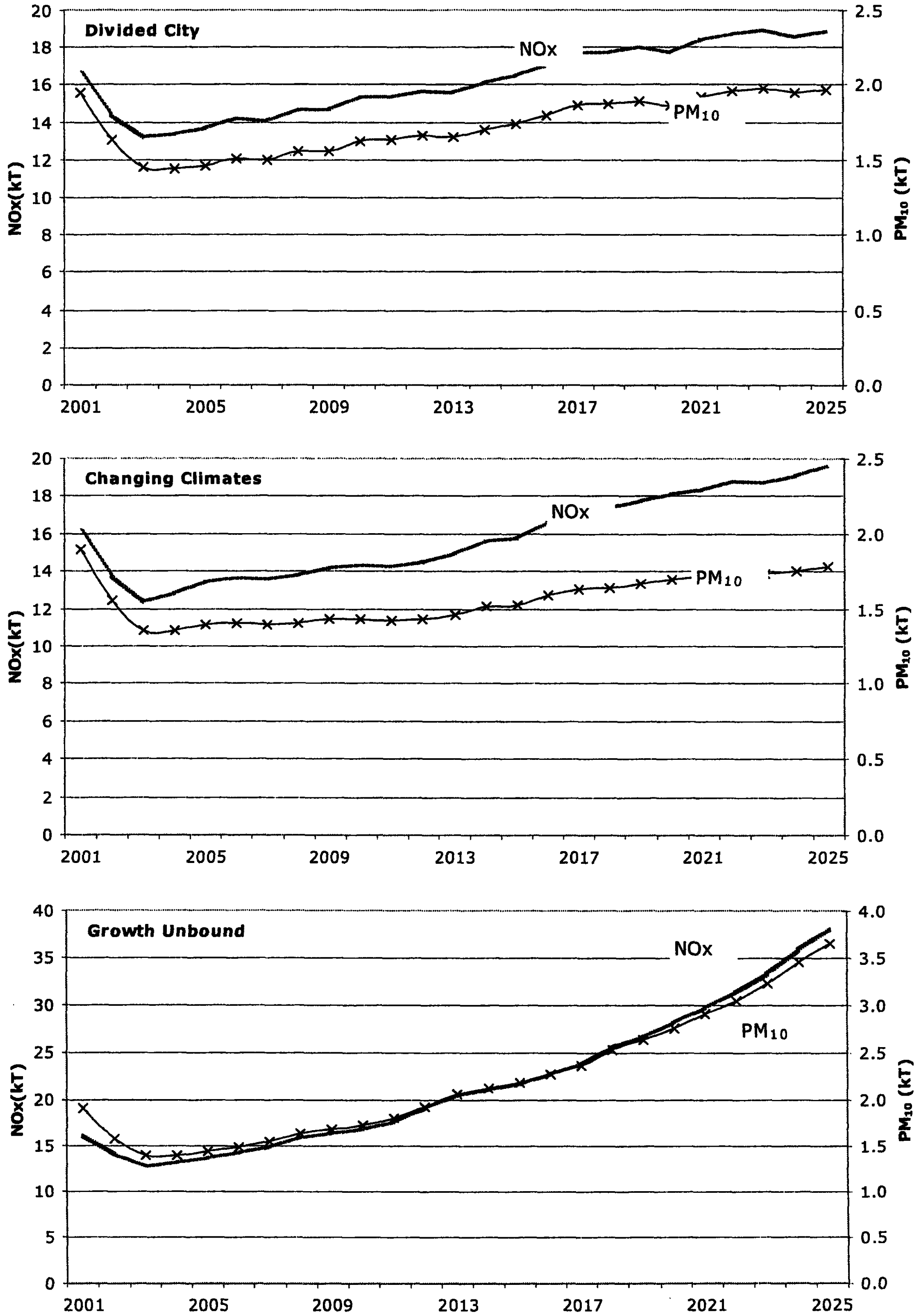


Figure 7.11 NO_x and PM_{10} Emissions for the Reference Scenarios



7.9.2 Performance of Option Bundles

In the reference case (DC-CUNULELI), the emissions of PM_{10} and NO_x will increase by 1 % and 14% respectively in 2025 (Table 7.12).

When we consider technology options alone, in PM_{10} emissions show moderated reduction from 2001 levels in two Future Stories, Divided City and Changing Climates. Whereas in the Future Story – Growth Unbound, none of the emissions show a reduction from 2001 levels. When we compare the percent change in emissions in 2025, we note that none of the technology options result in meeting the ad hoc goal of reducing emissions by 50% from the 2001 levels. Therefore, the conclusion that technology options alone, specifically, the end-of-pipe and process controls, are unable to meet the emissions reduction goal.

Next we look at the option bundle combining the end-of-pipe and process control technology options, with structure adjusted energy intensity reductions, and fuel-switching. The results in Table 7.12 show that for this option bundle, in the Future Story Changing Climates, show a substantial and sustained reduction in PM_{10} and NO_x emissions. And in Future Story – Growth Unbound, PM_{10} emissions show significant reductions.

When we consider only deindustrialization, Future Stories Growth Unbound and Divided City show substantial reduction in emissions of PM_{10} and NO_x. And when the technology and policy options are combined, all of the scenarios show a substantial reduction in emission in 2025 compared to the base-year (2001) emissions. Also note that the integrated strategy shows a 99% reduction in emissions in the Changing Climates Future Story, which is unrealistic, probably a result of the model not taking into account physical constraints of implementing the aggressive options.

Therefore, I conclude that the technology options alone do not meet the criteria of ad hoc target emission reductions. When combined with SAEI and fuel-switching, this option bundle results in substantial reduction, but not for all the Future Stories. Similarly, deindustrialization alone is unable to achieve substantial and sustained reductions. When all the technology and policy options are combined, all the scenarios result in meeting the ad hoc emissions reduction target.

In the next section, I carry out the tradeoff analysis to identify the cost-effectiveness of various strategies.

Table 7.12 Performance of the Aggressive Technology and Policy Options

	2025 Emissions		%Δ from 2001	
Scenario	PM_{10} (kt)	NO_x (kt)	PM_{10} (kt)	NO_x (kt)
Ref. Case (DC-CUNULELI)	1.96	18.83	1	14
Aggressive Technology Options Alone				
DC-CUNUHEHI	1.61	18.25	-17	10
CC-CUNUHEHI	1.38	18.77	-29	13
GU-CUNUHEHI	2.92	36.74	50	122
Aggressive Technology, Fuel Switch and SAEI Options				
DC-CUSAHEHI	1.10	13.02	-44	-21
CC-CUSAHEHI	0.31	6.29	-84	-62
GU-CUSAHEHI	0.80	11.42	-59	-31
Only Deindustrialization				
DC-RENULELI	1.05	9.95	-46	-40
CC-RENULELI	0.37	3.97	-81	-76
GU-RENULELI	1.47	15.20	-25	-8
Integrated Bundle of Aggressive Technology and Policy Options				
DC-RESAHEHI	0.54	6.24	-72	-62
CC-RESAHEHI	0.02	0.18	-99	-99
GU-RESAHEHI	0.54	1.80	-72	-89

7.10 Tradeoff Analysis

In the previous section, we analyzed various aggressive strategies (option bundles) in different Future Stories, to see if they are able to meet the ad hoc emissions reductions goal of 50% reduction from the 2001 level. In this section, I change the criteria of evaluation of various strategies, and consider cumulative emissions over the study period, as a basis to identify cost-effective strategies.

Table 7.13 shows the aggressive technology and policy options and their corresponding cumulative emissions and the net present value of the direct and policy cost for an inflation-free discount rate of 5%. Percent change in emissions and costs, with respect to the reference case (DC-CUNULELI) is also shown in the table. The results show that the cost of all the technology and policy options to reduce emissions is very high. Aggressive technology options alone show modest reductions in cumulative emissions of NO_x and PM_{10}, particularly for the two Future Stories, DC and CU. However, none of the aggressive technology options result in more than 50% reductions in aggregate emissions. Further, when the aggressive technology options are combined with fuel switching and SAEI reduction, the cumulative emissions show a significant decline over technology options alone. Cumulative emissions reductions in the case of deindustrialization are more than that in aggressive technology options alone. However, the policy cost, due to lost or foregone production is very high. The integrated aggressive options bundle show substantial reductions in aggregate emissions over the study period.

To plot the tradeoffs, I have calculated cumulative emissions of NO_x, and PM_{10}, for the study period ending in 2025, and shown it on the abscissa. The cost is shown on the ordinate. There are two kinds of tradeoff plots, using two different cost-measures. First, the capital cost, which uses the net present value of the total capital cost, invested during the model period, for a given strategy. The capital cost includes cost of capital investment for NO_x controls, capital investment for PM control equipment, the cost of improving energy efficiency, and operation and maintenance cost.

Table 7.13 The Performance of Aggressive Technology and Policy Options (Cumulative NO_x and PM_{10} Emissions and Costs)

	Cumulative Emissions		Net Present Cost (billion Pesos)	
Scenario	PM_{10} (kt)	NO_x (kt)	Direct	Policy
Ref. Case (DC-CUNULELI)	0.046	0.424	7.87	13.75
Aggressive Technology Options Alone				
DC-CUNUHEHI	0.039	0.414	19.63	54.51
CC-CUNUHEHI	0.032	0.396	33.43	77.14
GU-CUNUHEHI	0.046	0.544	27.46	68.24
Aggressive Technology, Fuel Switch and SAEI Options				
DC-CUSAHEHI	0.033	0.349	29.84	62.21
CC-CUSAHEHI	0.018	0.241	52.77	91.71
GU-CUSAHEHI	0.024	0.280	79.02	107.09
Only Deindustrialization				
DC-RENULELI	0.040	0.367	7.87	197.92
CC-RENULELI	0.029	0.281	21.61	272.96
GU-RENULELI	0.041	0.393	16.33	323.36
Integrated Bundle of Aggressive Technology and Policy Options				
DC-RESAHEHI	0.029	0.306	29.84	246.38
CC-RESAHEHI	0.015	0.179	52.77	333.92
GU-RESAHEHI	0.018	0.198	79.02	406.04
Percent Change from the Reference - DC-CUNULELI				
Aggressive Technology Options Alone				
DC-CUNUHEHI	-14	-2	149	296
CC-CUNUHEHI	-31	-7	325	461
GU-CUNUHEHI	2	28	249	396
Aggressive Technology, Fuel Switch and SAEI Options				
DC-CUSAHEHI	-28	-18	279	352
CC-CUSAHEHI	-60	-43	570	567
GU-CUSAHEHI	-47	-34	904	679
Only Deindustrialization				
DC-RENULELI	-13	-13	0	1339
CC-RENULELI	-36	-34	175	1885
GU-RENULELI	-10	-7	107	2251
Integrated Bundle of Aggressive Technology and Policy Options				
DC-RESAHEHI	-35	-28	279	1692
CC-RESAHEHI	-68	-58	570	2328
GU-RESAHEHI	-60	-53	904	2853

Another variable I use to carry out tradeoffs analysis is policy cost, which is the net present value of the sum of the capital cost, O&M cost, and air quality program implementation cost, and the cost due to lost output, as given by Equation 7.2. When the industrial output reduces, the demand for intermediate goods and services also reduces, thereby affecting overall value of the goods produced by the economy. Moreover, the reduction in demand or output can have secondary and tertiary impacts, such as loss of jobs in the region. However, in this analysis all those secondary and tertiary impacts of reduced industrial output are not included, as input-output framework for the MCMA is not available to estimate such impacts on the economy.

7.10.1 Policy Cost versus Direct Cost (Capital, O&M, AQP)

The choice of cost measure affects the selection of the robust strategies or options to reduce emissions in a cost-effective manner. Therefore it is important to choose correct cost metric for the tradeoff analysis. We have estimated two cost-measures to identify robust strategies. Direct cost, includes the cost of renewing capital stock, affecting energy efficiency, and the investment in control technologies. Policy cost is a super-set of the direct cost, and in addition to all the components included in direct cost, it also includes the cost of forgone industrial output.

It might be possible for a policymaker to craft policies to shift manufacturing activities from one region to another by instituting the right incentives. However, the foregone industrial production is not the only effect of deindustrialization policies. The lost industrial output of a region can be compensated by increasing output from another sector (or another region) of the economy, such as commerce and services. However, deindustrialization also affects number of jobs in a region, which is a very sensitive issue from political feasibility perspective. Therefore, using total policy cost might be a better cost metric to evaluate the technology and policy options in certain situations. In this study I have calculated both, the direct cost and total policy cost, for each of the strategies.

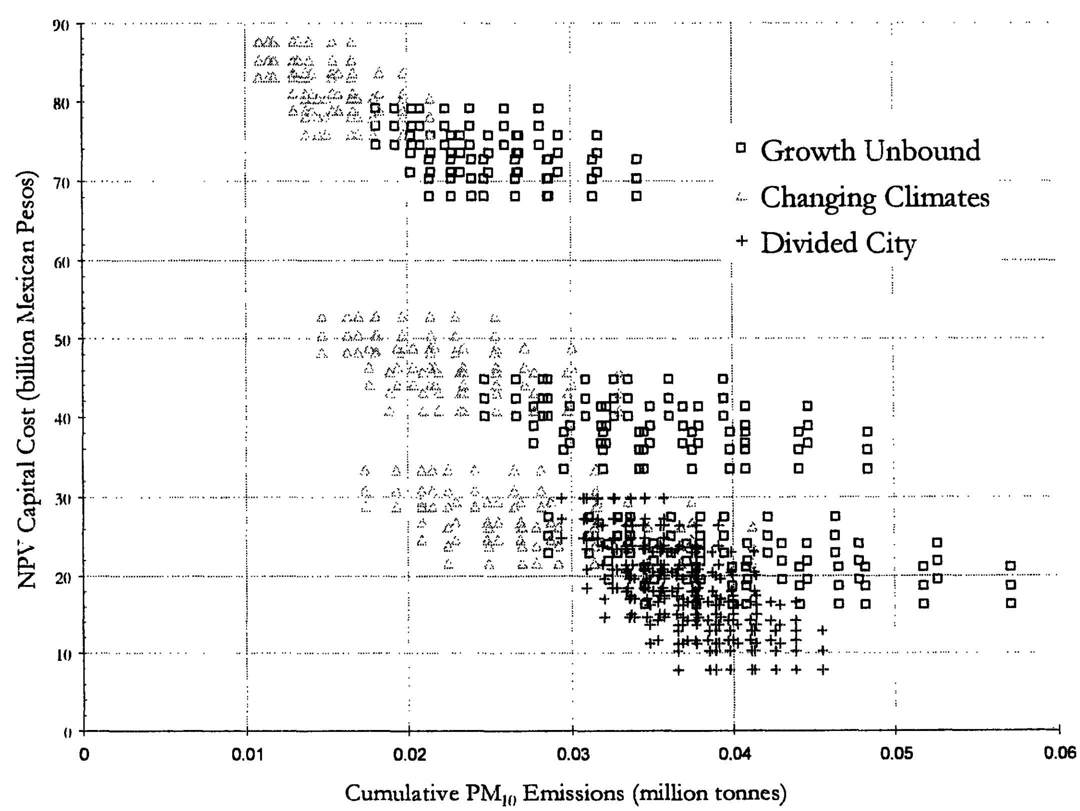
7.11 Identifying the Robust Strategies

In order to identify robust strategies, we analyze how changing some of the key variables affect the performance of select strategies. First, we investigate how Future Stories, or the uncertainty affect performance of certain strategies. Next, we will look at the cost metric, and see how different strategies shift with change in the cost-metric. Further, we will see impact of change in the pollutant, from NO_x to PM_{10}, or vice-versa.

7.11.1 Impact of Future Stories

The impact of Future Stories is indicated by the tradeoff plots shown below.

Figure 7.12 Impact of Future Stories on Strategies

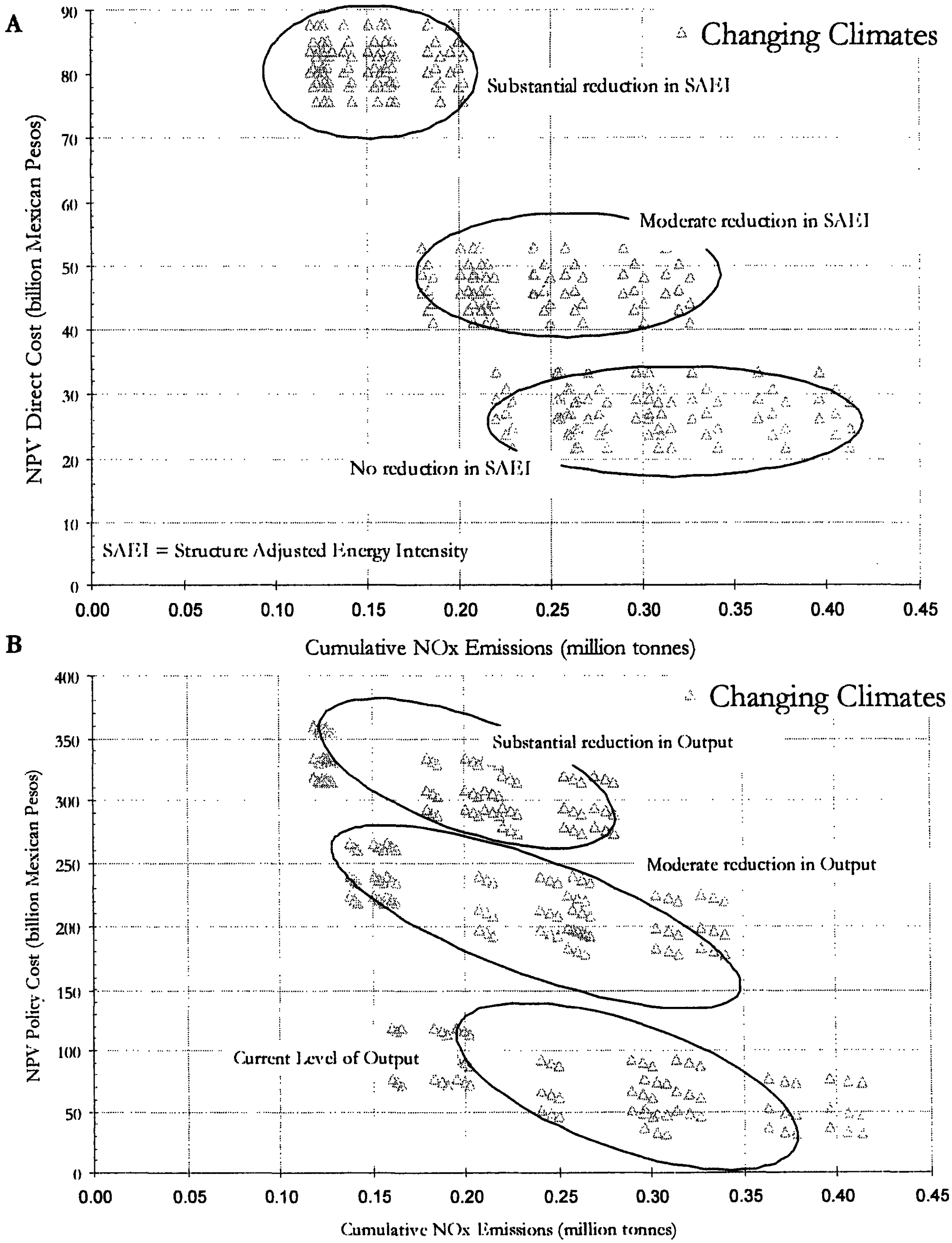


We note that strategies are clustered in multiple groups for Future Story, Changing Climates and Growth Unbound, and the range of cumulative emissions over the study period is also wider in these two Future Stories. Note that the cumulative emissions reduce in most of the strategies when Future Story changes from GU to CC, at the same time, the net present value of the abatement cost also increases. The movement of the strategies in clusters indicate that the strategies that are robust in one Future Story, are also on the tradeoff frontier for another Future Story.

The range of cumulative NO_x emissions in the Future Story - Divided City is 0.3 to 0.42 million tonnes of cumulative emissions of NO_x. The net present value of the capital investment ranges between 8 billion Mexican pesos to 30 billion pesos. The cumulative NO_x emissions in the CC Future Story range from 0.12 to 0.43 million tonnes. The net present cost of capital investment ranges from 22 to 89 billion Mexican pesos. The CC Future Story shows significant reductions in NO_x emissions as compared to the DC. Moreover, the CC strategies are clustered in several groups. In the next sub-section, we examine the clusters for a given Future Story, and identify the technology and policy options that drive the formation of clusters. We choose the Future Story - Changing Climates, and plot NO_x emissions on the x-axis, and on the y-axis, the capital or direct cost is plotted (see Figure 7.13).

For NO_x emissions, one would expect the clustering to be around the option, End-of-pipe NO_x controls, but we note that the three clusters are differentiated by Structure Adjusted Energy Intensity (SAEI). This can be interpreted as cumulative NO_x emissions reductions being most sensitive to the energy intensity changes and shift in the industrial structure, in the MCMA. Also, the clustering is a function of the cost metric, as demonstrated below. We have kept all the same variables as in the Figure 7.12, and changed the cost attribute from Direct (Capital) cost to total policy cost, and the clustering is around the policy option deindustrialization. The three clusters correspond to different levels of deindustrialization.

Figure 7.13 Clustering of Strategies for NO_x (Future Story - Changing Climates) A) Direct Cost B) Total Policy Cost



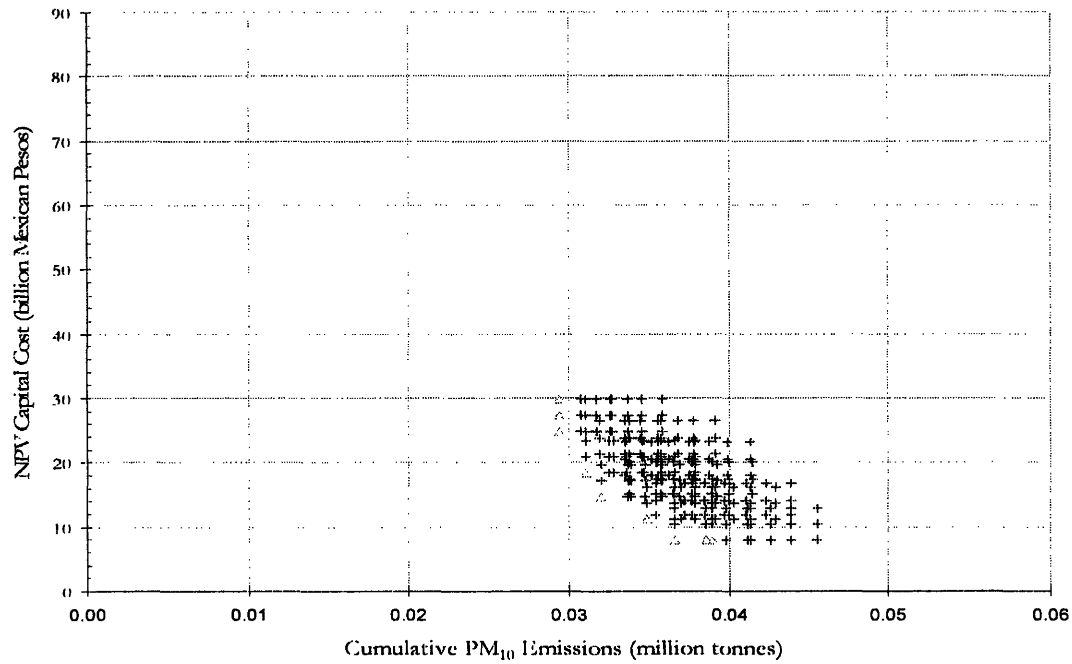
7.11.2 Impact of Different Pollutants on Strategies

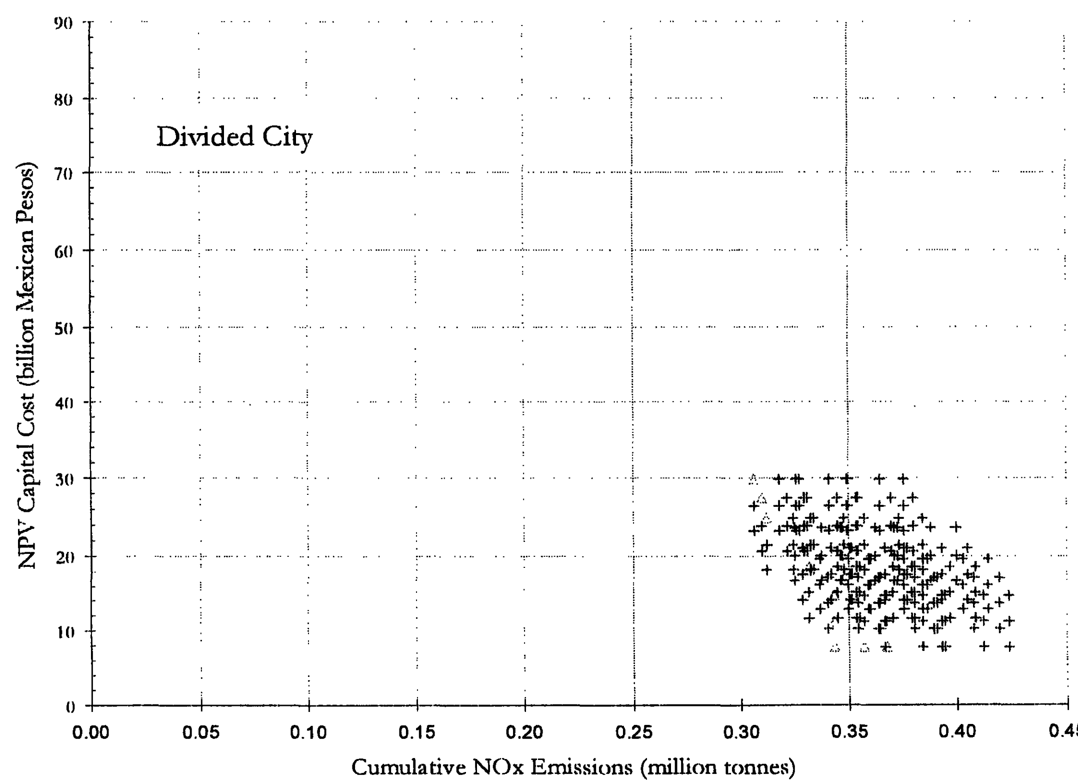
The strategies on the tradeoff frontier for one pollutant may shift once we change the pollutant. Since this research mostly focuses on strategies to reduce NO_x and PM_{10} emissions, we investigate the impact of changing the pollutant on positioning of strategies on the tradeoff plot. We choose, a few strategies on the tradeoff plot for Future Story – Divided City, for pollutant PM, and cost attribute being the direct or capital cost.

The "+" symbol indicates various strategies, and the "Δ" symbol indicates the strategies on the tradeoff frontier. We note that there are no groupings of options for NO_x reduction, indicating no particular variable dominating the tradeoff plot (Figure 7.14).

When we change the pollutant from PM to NO_x, the most cost-effective strategies are no longer on the tradeoff frontier. However, the strategies on PM tradeoff frontier still fare better than most of the others, when considering NO_x (Figure 7.14 (B). The cost associated with NO_x or PM controls causes this relative shift, but overall the same frontier can be used to choose the cost-effective strategies. This indicates that the strategies on the tradeoff frontier are not very sensitive to change in the pollutant, i.e., a cost-effective strategy for one pollutant will also reduce another pollutant. This result is clearly indicates dominance of policy options such as structural shift and energy intensity reduction, as opposed to the technology options, end-of-pipe NO_x and PM controls.

Figure 7.14 Impact of Pollutant on Tradeoff Frontier A) Tradeoff Frontier for PM_{10} Emissions. B) Tradeoff Frontier for NO_x Emissions



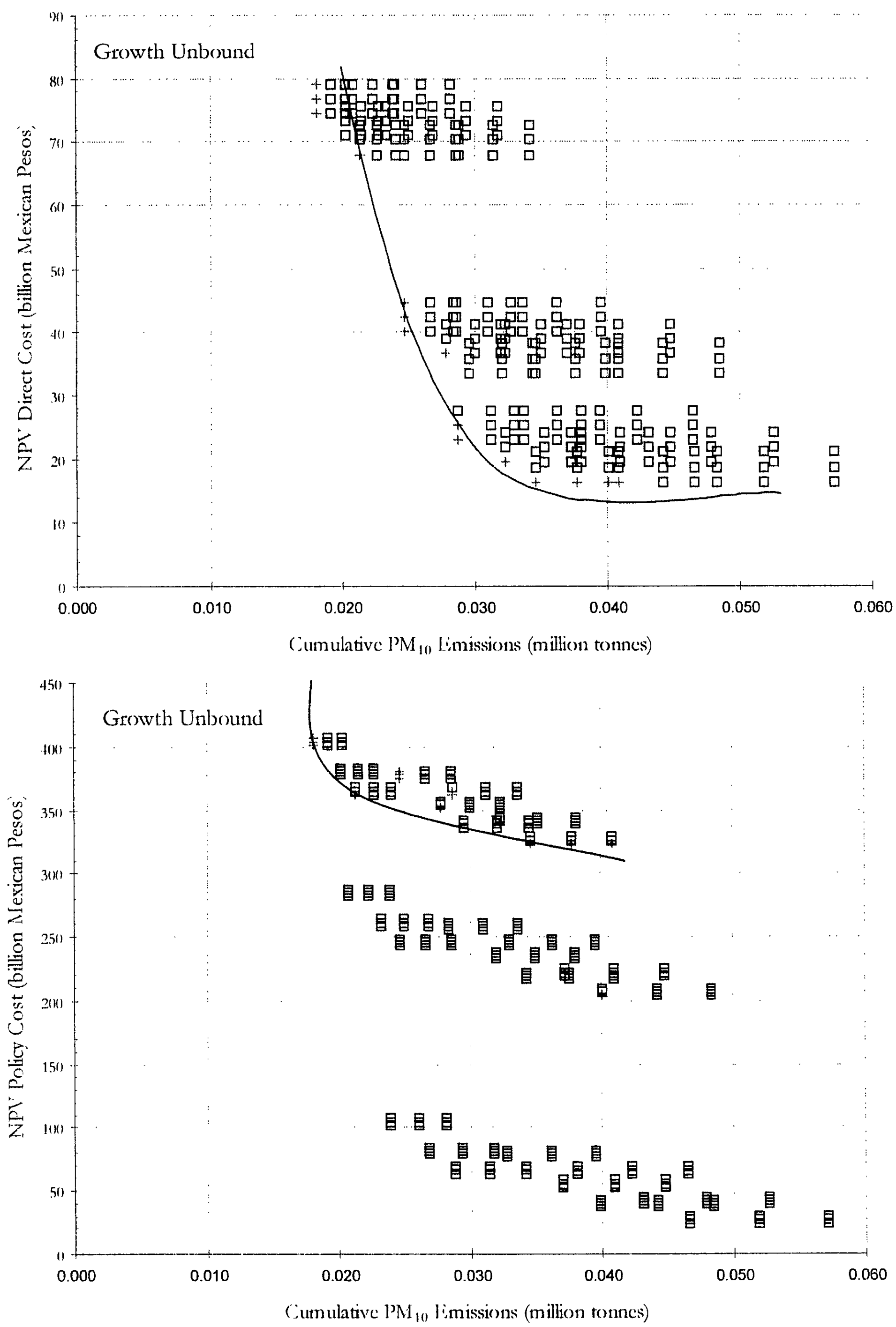


7.11.3 Policy Cost and Tradeoff Frontier

We briefly discussed the impact of varying cost attribute from direct cost to policy cost above. In this section, we plot the tradeoff frontiers for direct cost and total policy cost. We note that the strategies on frontier could significantly shift if the cost-measure is changed from the direct capital cost to the total policy cost. As indicated earlier, the total policy cost includes the cost of foregone production as a result of the deindustrialization policy. The impact on the tradeoff plot is demonstrated in Figure 7.15 (A) and (B). In Figure 7.15, tradeoff frontier is shown by symbol "+" for scenario GU. When we change the cost metric from capital to policy cost, the tradeoff frontier has significantly shifted, in-fact it is no longer a frontier, but different points on the tradeoff plots. Only a few points from the previous tradeoff plot in Figure 7.15 (A) show as cost-effective set of options on the plot when we use total policy cost.

The clusters are grouped around the variable, industrial output from the industries. The significant reduction in the emissions can be achieved at the opportunity cost of foregone production. However, the cost of doing so can be significant, as compared to the options such as reducing structure adjusted energy intensity.

Figure 7.15 Impact of Cost-metric on the Tradeoff Frontier A) Direct Cost, B) Policy Cost



7.12 Summary and Conclusions

In this chapter, I conducted the tradeoff analysis and analyzed performance of the strategies resulting from combination of different values of options. I used two cost metrics, direct cost and policy cost, to evaluate relative performance of the strategies for industrial emissions reduction over the study period 2000-2025.

Using the model developed in Chapter 5 I estimated emissions of air pollutants, by incorporating various technology and policy options. Specifically, I included the impact of changes in the energy intensity, structure of the industry, fuel-switching, exogenous growth rate of industry sector, policy influenced growth rate of the MCMA industry, end-of-pipe and process NO_x controls, and PM controls to estimate emissions for various scenarios.

Emissions estimations for the period 2001-2025 indicated that due to the strong influence of the factors affecting industrial growth in the MCMA, emissions are likely to increase significantly in most of the scenarios. Even the most aggressive implementation of the technology and policy options could not achieve the ad-hoc emissions abatement target of 50% reduction from the current (2000) levels in year 2025.

Only those scenarios where aggressive implementation of options, such as introduction of fuel-switching, end-of-pipe controls were coupled with low or modest growth of industrial output were able to achieve significant reductions in emissions from the current levels.

I estimated the emissions for each bundle of options (also referred as a strategy) for each year for the period 2000-2025. Further, I estimated cumulative emissions for the 25 year period for two pollutants of interest, PM10 and NO_x. The cost of implementation of the options was also estimated. I then estimated two metrics of costs, a direct capital cost, which included cost of installation, operation and maintenance of end-of-pipe and process controls, and policy cost, which also included opportunity cost of foregone industrial output as a result of a targeted deindustrialization policy.

Tradeoff frontiers were drawn to analyze the implications of various strategies and their cost-effectiveness under different Future Stories. The performance of strategies was found to be very sensitive to the choice of cost metric. The two cost metrics resulted in different conclusions. When only direct cost is considered, the deindustrialization options turn out to be cost-effective, as opposed to reduction in the SAEI option when the policy cost is considered.

Future Stories had a significant impact on cost-effectiveness of a strategy. Except in the Future Story - Divided City, the strategies were clustered in other Future Stories, around one dominant option-variable. Structure Adjusted Energy Intensity (SAEI) emerged as the most dominant variable affecting the relative positioning of strategies when direct cost was used to analyze performance of strategies.

The strategies on the tradeoff frontier corresponding to one pollutant did not necessary fall on the tradeoff frontier for the other pollutant. However, generally the strategies which were performed well for reducing cumulative emissions for one pollutant (PM_{10}) were also effective for reducing emissions in a cost-effective manner for the other pollutant (NO_x). Therefore, we can conclude that robust strategies for one pollutant are cost-effective for the other pollutant as well.

The Choice of the cost metric played a key role in determining the cost-effectiveness of strategies. A strategy on a tradeoff frontier when considering capital cost, did not find a place on the tradeoff frontier, when the total policy cost was considered. This demonstrates sensitivity of strategies to the cost measure.

When the total policy cost was considered, deindustrialization was the most dominant policy in reducing cumulative industrial air pollution. Fuel-switching was another important variable that appeared in most of the cost-effective strategies.

In the next chapter, I estimate savings from the use of market-based instruments, to achieve abatement by incurring the least-cost. Particularly, I argue that savings achieved from the use of market-based instruments (MBIs) could be significant and could be a key driver for the push to implement the flexible MBIs.

Chapter 8

Heterogeneity of Abatement Cost and Savings from the Use of Market-Based Instruments

In the previous chapter, I presented the results of emissions estimates and cost of various technology and policy options, to reduce emissions from the Mexico City Metropolitan Area (MCMA) industries. The abatement goals can be achieved by either using a command-and-control approach to dictate technology standards, or by giving flexibility to industry to achieve abatement goals through the use of market-based instruments.

In this chapter, I examine and estimate the cost implications of uniform abatement policies (command-and-control), and savings from the use of market-based instruments by applying the equimarginal principle[1], in achieving different abatement levels by firms in such a way that their marginal abatement cost (MAC) is equal.

We know that if there are many polluters with different MAC, then we should employ a regulatory approach where those emitters with lower control cost reduce their emissions first. In theory, this sounds right, but in practice, it poses many difficulties. First, there exists asymmetry of information between a regulator and polluter, and it is almost impossible for a regulator to find out the exact MAC for a given facility, firm or industry. Second, even if a regulator knew the exact MAC for polluters, implementing a policy that calls for heterogeneous abatement would ruffle quite a few socio-political feathers. Third, it might be too expensive for the regulator

[1] The equimarginal principle calls for reducing emissions by all participants to a level where the marginal abatement cost of all participants is equal.

to determine, allocate and monitor emissions for each of the polluters. The market-based instruments (MBIs), such as tradable permits, allow a regulator to achieve emissions reductions at the lower overall cost, thereby maximizing social welfare. However, success of tradable permits depends on the creation of a competitive and efficient market for permits. Of late, the use of market-based instruments to achieve environmental goals have become more acceptable. But policy makers need to have reasonable estimates of the cost savings before they can seriously pursue adoption of MBIs. For example, if I try to sell the idea of using marketable permits to a politician, on the basis of efficiency, the first question she will ask is, "OK, how much will be the cost or what will be the savings from the use of market-based instruments?" When a policy maker needs to choose between command-and-control approach and the market-based approach, she would like to know if the trouble is worth taking, i.e., if the savings from the market based approach are more than the costs to create an efficient market for tradable permits.

To answer the above question, in this chapter, I estimate savings from implementing a market-based approach for abatement of NO_x, PM, and SO_x pollution from the MCMA industrial sector by applying the equi-marginal principle.

I estimate costs of emissions abatement for the following three cases: first, when the burden of abatement is distributed in a uniform manner among all the sub-sectors, second, when the burden of abatement is distributed such that each of the sub-sectors reduces a given percentage of emissions, i.e., if the total abatement goal is 10%, then each sector reduces 10% emissions from their current levels, and third, when the burden of abatement is distributed on the basis of the equimarginal principle.

Table 8.1 lists the abatement costs for different pollutants, for nine industrial sub-sectors. The abatement costs were estimated by Hartman and Wheeler (1997) on the basis of data collected from the US manufacturing industries. The table indicates that the cost of abatement of NO_x is the highest for the textile sub-sector, followed by non-metallic minerals and basic metal industries. In comparison, the abatement cost of NO_x for chemical sub-sector is very low. The chemical sub-sector is one of the leading polluters in the MCMA industrial sector.

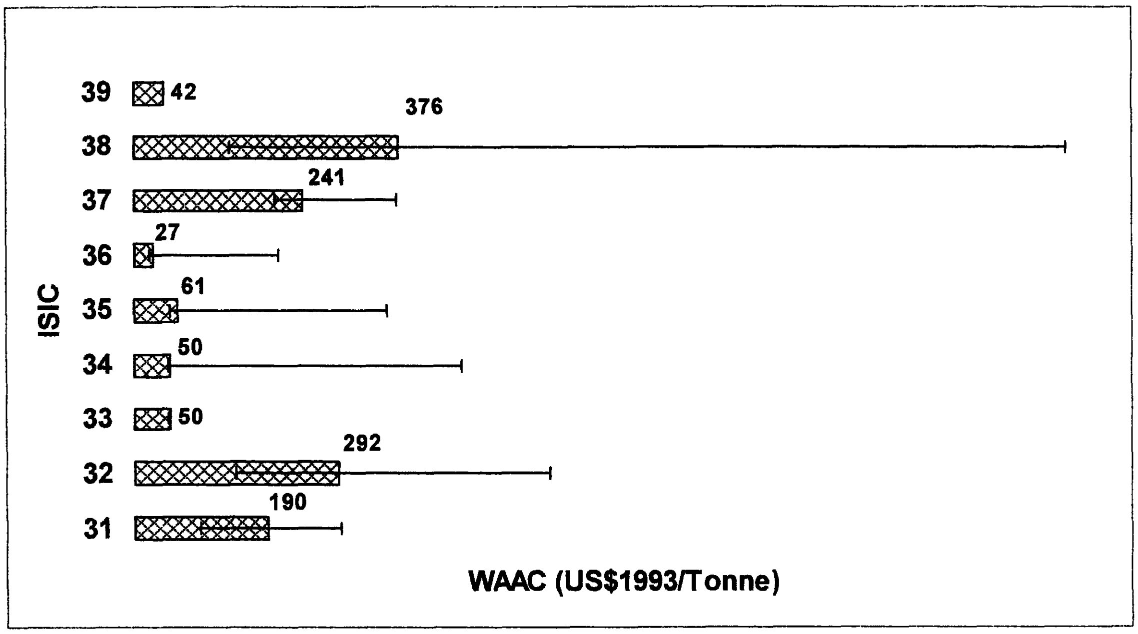
Table 8.1 Weighted Average Abatement Cost for 2-Digit Industry Sectors (US$ 1993/Tonne)

ISIC	Sector	PM	SO_2	NO_x
36	Non-Metallic Minerals	27.42	249.93	1504.04
39	Other Manufacturing Industries	41.89	28.66	121.25
33	Wood and Wood products	49.57	36.27	31.14
34	Paper, Paper Products, etc.	50.35	177.42	264.84
35	Chemicals, Coal, Rubber, Plastic Derivatives, etc.	60.52	137.10	93.29
31	Food products, Beverages and Tobacco	190.21	341.04	833.91
37	Basic Metal Industries	240.91	242.73	124.51
32	Clothing, Textiles and Leather Products	291.78	528.71	2147.02
38	Metallic Products, Machinery and Equipment	376.20	1180.48	1113.66

ISIC = International Standard Industrial Classification
PM = Particulate Matter
SO_2 = Sulfur dioxide
NO_x = Oxides of Nitrogen, generally represented as NO_2
HC = Hydrocarbons
Source: Adapted from Hartman et al (1997)

For PM emissions abatement, the metal products industry pays the highest cost on a per tonne on a particulates removed basis. Textiles and basic metal industries have lower cost of PM abatement than the metal-products sector. Figure 8.1 shows the range of particulate abatement cost for different sub-sectors, by their international standard industrial code (ISIC codes). Sub-sector description corresponding to the ISIC codes is presented in Table 8.1.

Figure 8.1 Range of Weighted Average Abatement Cost for Particulates



Source: Hartman and Wheeler (1997)

8.1 Data Sources

Ideally, one would like to know the exact emissions from all the sources in question and their MAC curves to apply the equimarginal principle and determine the exact abatement responsibility for each of the sources, and then calculate the total abatement cost. However, it is almost impossible to determine the exact marginal abatement curve for each individual firm. Therefore, I use an alternative approach to estimate abatement cost.

I obtained annual emissions data for the year 2000 from a database prepared by the Metropolitan Environmental Commission (*Comisión Ambiental Metropolitana* or CAM) of the MCMA. The database aggregates firm level emissions of about 6200 facilities located in the MCMA and presents it at the two-digit industry sector level. The database is a compilation of mandatory filing requirements, whereby each firm is required to report its annual schedule of operations (*cédula de operación* or COA), which contains data pertaining to the quantity of output produced by the firm, fuel consumed, and annual emissions of criteria pollutants, etc. There are several problems with the database, but for the purpose of this analysis, emission data for each individual sub-sector is taken as reported in the emissions inventory.

Emissions for the nine categories for the target pollutants, NO_x, SO_2, and PM_{10} are presented in Table 8.2

8.1.1 Abatement Cost Data

Since no abatement cost data is available for the nine sectors in the MCMA, I use abatement cost data for US industry. The World Bank sponsored an effort to determine the cost of abatement for different industries. The World Bank Pollution Abatement Costs and Expenditures (PACE) survey-instrument was designed and data for more than 20,000 industries in the US was collected over a period of 5 years. A sectoral analysis of the data on the basis of industrial classification codes was done by Hartman and Wheeler (1997). Hartman et al. further combined this data with the US Industrial Census data to obtain a more comprehensive estimate of emissions abatement costs. The Hartman and Wheeler abatement cost data for various pollutants is based on 4-digit industry codes, which does match with the Mexican industry 9-sector classification, used by the emissions inventory (CAM 2004). The sectoral abatement cost data was presented in Table 8.1.

The abatement cost data may not be an exact fit for the Mexican industry, because there may be country-specific structural differences in the abatement cost, such as labor costs, which is quite different for the US than Mexico. Also, the data collected for the US industry is not recent, and advances in science and technology of air pollution control may have reduced the cost of pollution control. However, if we assume that the abatement cost has two major components, capital and labor, and treat the abatement technology to be uniform in Mexico and the US, then cheaper labor in Mexico is likely to cause an upward bias in the abatement cost data from using the PACE survey data for the US. Similarly, technical change and innovation may also cause an upward bias (overestimation of abatement cost). However, the abatement cost data should give us a good upper bound or conservative estimates of the cost of abatement. Thereby, the savings achieved can be said to be minimum savings that we can expect from adopting a policy which would enable differential abatement such that the marginal cost of abatement for the nine sectors is equal.

8.2 Abatement Estimation Methodology

For a single pollutant, such as NO_x,

Let the total abatement of the pollutant required by the regulator from the MCMA's industrial sector be: Q_A

Let abatement responsibility of each sector be: Q_j

Let the sectoral MAC be: $MC_j = \alpha_j Q_j$

Where α_j is the average abatement cost of sector j for a given pollutant (as given in table 8.1).

For cost effective allocation of abatement responsibility, marginal abatement costs should be equal, therefore,

$$MC_j = MC_k \qquad j, k, \text{ such that } j \neq k$$

Total abatement constraint:

$$\sum Q_j \geq Q_A$$

Subject to,

$$Q_j \leq E_j, \forall\, j$$

Where E_j is current emission levels of sector j

Total abatement cost can be estimated as:

$$\sum_j \int_0^{Q_j} MC_j dQ \qquad \textbf{(8.1)}$$

I use Microsoft Excel's optimization routine Solver® to solve the aforementioned equations, subject to the appropriate constraints, and obtain the abatement level of each industrial sector using the equimarginal principle. Then I calculate the total abatement cost by calculating the abatement cost for each sector, depending on the level of abatement, for all the 9 sub-sectors.

For equal abatement by each of the sectors, the abatement responsibility is $Q_A/9$ for each sector.

For estimating cost for equal percentage of abatement by each sector, the abatement responsibility is expressed as, $E_j \times Q_A$ / Sum (Ej) for all j.

8.3 Savings from Different Policy Options

I calculated the cost of abatement for the following three cases:

- The burden of abatement is distributed in a uniform manner among all the sectors, i.e., for a given abatement goal of Q_A, each sector is responsible for abatement of $Q_A/9$.

- The burden of abatement is distributed such that each of the nine sectors reduces a given percentage of emissions, i.e., if the total abatement goal is 10%, then each sector reduces 10% emissions from their current levels.

- The burden of abatement is distributed on the basis of the equimarginal principle, i.e., each of the 9 sectors reduce emissions such that their MAC is equal, and total abatement constraint is satisfied.

Figure 8.2, shows the resulting abatement burden of the different sub-sectors using equi-marginal principle for particulate matter. If the abatement goal is 40%, then non-metallic mineral sub-sector is expected to reduce over 250 tonnes of particulate matter, closely followed by the chemical sub-sector which reduces about 215 tonnes of its PM emissions.

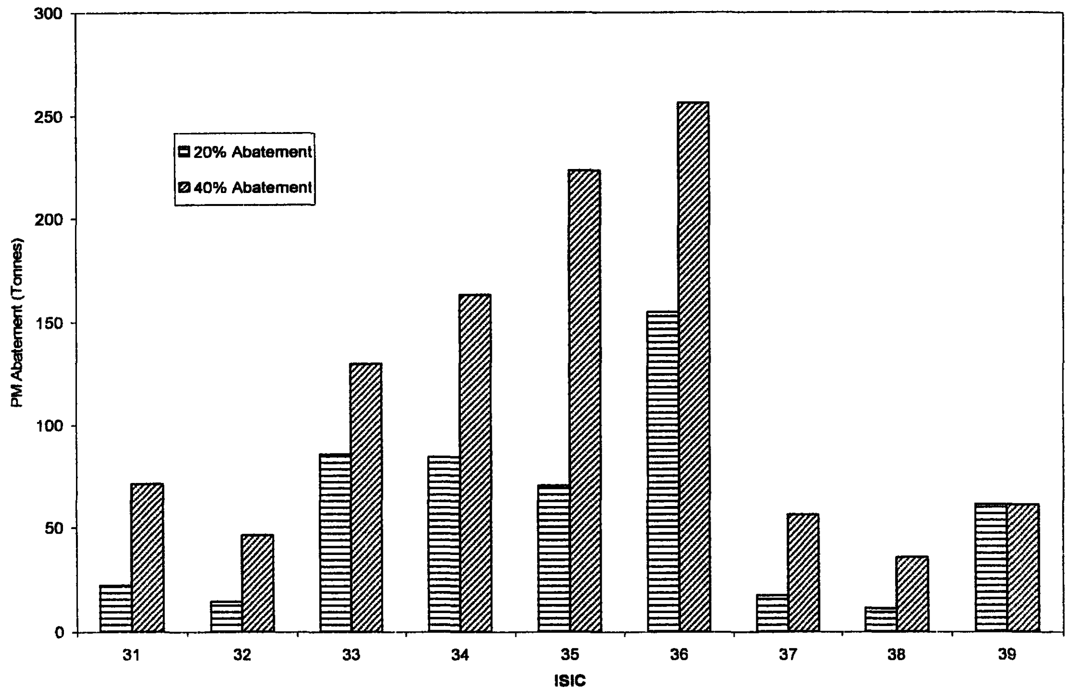
Figure 8.2 also shows percentage abatement achieved by each of the sub-sectors for a 20% and 40% of total reduction. For a 40% abatement of total particulate matter in the MCMA, several sub-sectors, such as wood & wood products, paper & printing, non-metallic minerals, will have to reduce their emissions by about 100%, which is an unrealistic goal.

Abatement cost for particulate emissions for different levels of abatement is shown in Figure 8.3. About 30% particulate abatement target can be achieved at the cost of 2 million 1993 USD. However, as the abatement goals become more aggressive, such as 40% or 50%, it becomes very expensive to achieve additional reductions.

Figure 8.4 shows initial levels of emissions for each sub-sector (unabated emissions), and also shows emissions from the same sector after achieving 20% and 40% abatement target. On the secondary axis the abatement cost is plotted to demonstrate that the sub-sectors for which abatement cost is low, achieve high levels of abatement, resulting in overall a cost-effective solution.

Table 8.3 lists the total abatement cost for particulate in the MCMA for the three different policies, first, when each of the sub-sector is asked to achieve equal abatement. Second, when each of the firm or facility is asked to achieve abatement target in proportion to their base-line emissions. Finally, the third case in when each firm reduces its emissions until the abatement goal is achieved or its marginal cost of abatement becomes equal to that of all the other polluters.

Figure 8.2 Distribution of Abatement Responsibility of Particulates among Industry Sectors Using Equi-marginal Principle



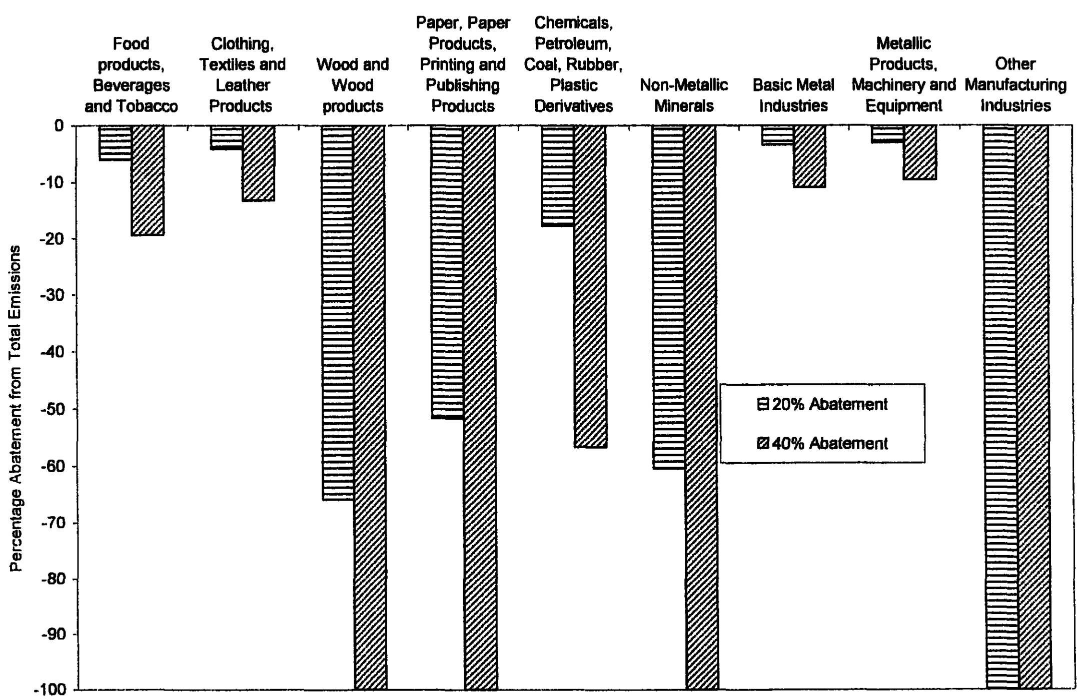
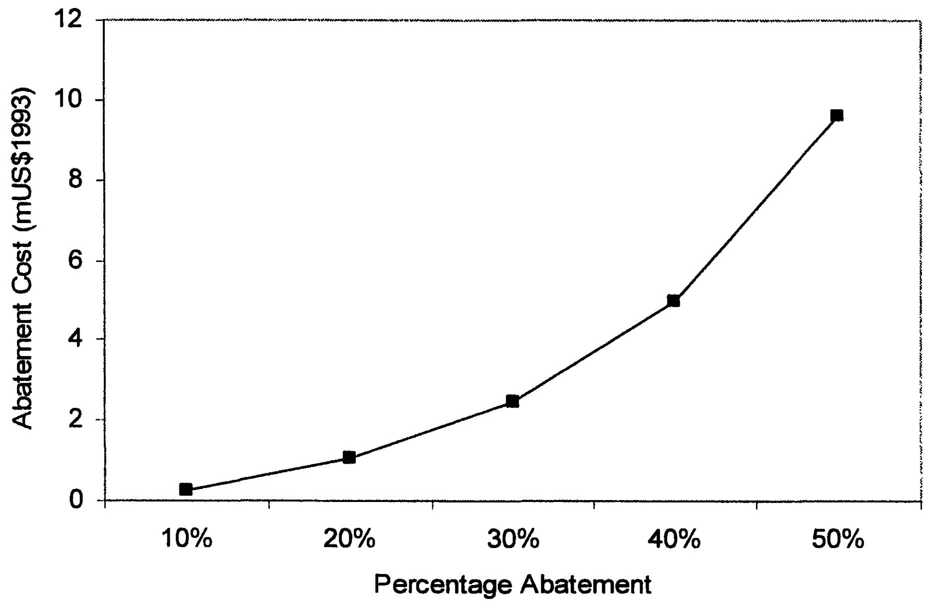


Figure 8.3 Abatement Cost for Particulates for Various Abatement Levels



For a given level of abatement, say 20%, the cost of achieving equal percent reduction is estimated to be $3.82 million 1993 USD, as opposed to only 1.05 million 1993 USD, a 75% reduction, when applying equi-marginal principle to achieve abatement targets in an efficient manner. The difference in the abatement cost is also shown in Figure 8.5.

Figure 8.4 PM Emissions for 20% and 40% Abatement Level, and Cost of Abatement

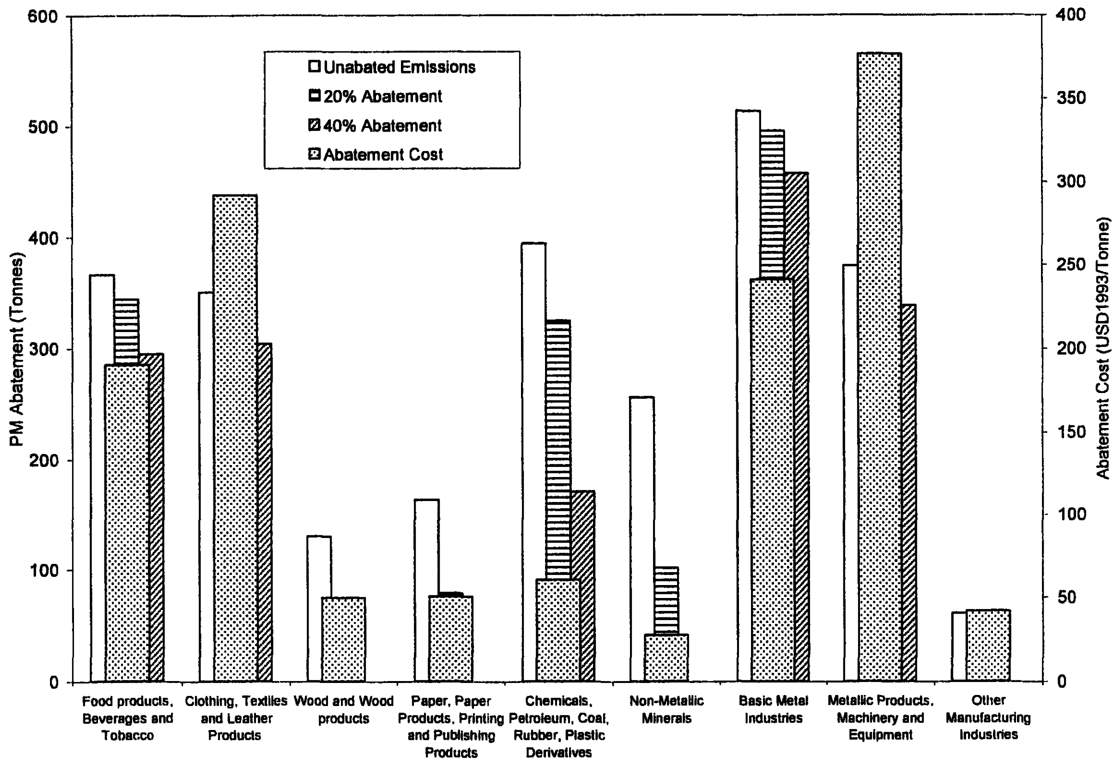
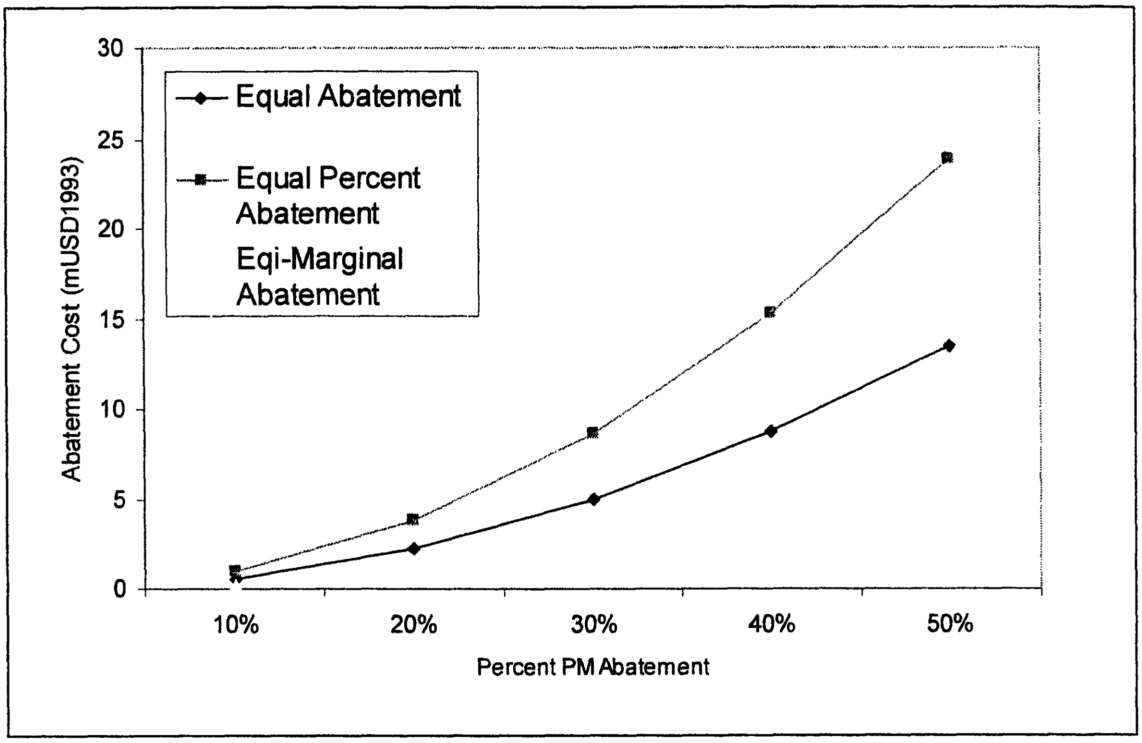


Table 8.2 Level of PM Abatement and Cost of Abatement (mUSD 1993)

Abatement Level	Abatement (Tonnes)	Equal Abatement (mUSD1993)	Equal Percent Abatement (mUSD 1993)	Eqi-Marginal Abatement (mUSD 1993)
10%	260.70	0.56	0.95	0.26
20%	521.40	2.23	3.82	1.05
30%	782.10	4.94	8.58	2.47
40%	1042.80	8.72	15.26	4.99
50%	1303.50	13.47	23.85	9.57

Figure 8.5 Abatement Cost for PM (mUSD1993)



8.4 Limitations of the Analysis

There are many assumptions and simplifications in this analysis, some of which have been discussed in the previous 3 sections, and some of which are discussed here.

First, I have assumed that the target pollutants in question, NO_x, PM, and SO_x, are uniformly mixed pollutants, and their spatial and temporal distribution does not make any difference to the policy maker. This assumption is not necessarily true, as NO_x reacts with hydrocarbons at various elevations in different manners due to different amounts of sunlight present. Moreover, at certain times of the day, NO_x emissions are good; in a certain proportion, it actually helps in dissociating the ozone. However, this phenomenon is too complex to be modeled and incorporated in this analysis.

I have lumped industries of different sizes, producing different output, using different inputs, and being located at different places. In its reduced form, I am essentially analyzing 9 different big sources (industry sub-sectors) within an air- shed, with different marginal abatement costs. Although data from Hartman and Wheeler supports the assumption that heterogeneity of abatement cost within a given sector is less than that between different sectors, it certainly cannot be uniform across different firms within a given sector. A small difference in input such as fuel type, say, natural gas and diesel, would make a huge difference in emissions from the two sources within a given sector, and therefore the abatement cost will also be different.

The functional form of MAC that I have used is linear, leading to a quadratic form of total abatement cost function, which may not be the case in reality. I have used the average abatement cost estimates as coefficients for my MAC function. Per tonne cost of emission does not reflect the actual nature of investment in the abatement technology by a firm, which is more likely to give a step function kind of discontinuous abatement cost curve, than a smooth quadratic curve.

Retrofitting of the ISIC codes to the Mexican sectoral data may have caused some error. The direction of the bias introduced thus may be difficult to know. A more refined approach could have been to assume a distribution of the industries in a given sector, and then calculate the abatement cost distribution from the average abatement cost and standard deviation. The abatement cost data can also be obtained from other sources, and broken into capital and variable cost components, to see how changing the variable component would affect abatement costs for the MCMA.

Also, I have not discussed how the tradable permits or other instruments could be implemented to achieve the equimarginal abatement from all sources. Initial allocation of the permits, if they are allocated or grand-fathered, could have significant distributional impacts and may be very important from a policy perspective. However, if initial permits are auctioned, it may be possible to avoid such impacts, but it will introduce additional cost considerations.

Continuous emissions monitoring of SO_2 emissions from utilities played a significant role in the success of the emissions trading program in the US. The cost of such emissions monitoring may be a stumbling block for policy makers interested in adopting a market-based approach in the MCMA. Therefore such a cost should also be taken into account while calculating savings from the MBIs.

Demonstrably emissions reductions obtained from the other source categories, such as transportation and households, and their abatement cost, have not been considered.

The analysis presented here clearly indicates the superiority of the market-based instruments in achieving the emissions reduction objective at the least cost to the society.

8.5 Policy Implications for the MCMA

In this chapter, I used a sectoral approach to apply equi-marginal principle to the firms and the MCMA to estimate potential savings from the use of market-based instruments.

The main argument in continuing to use the conventional methods is: it is very expensive to create markets for emissions trading or otherwise encourage the use of other market-based instruments. There are significant transaction costs associated with the use of market-based instruments. One key component is the need for having a reliable emissions monitoring system set up, and property rights (in terms of ability to pollute) clearly defined and enforced.

If the savings achieved by the use of market-based instruments is greater than the potential cost of creating the markets (or transaction cost) then there is a strong case for the use of MBIs to achieve the emission abatement targets in a cost effective manner.

In this research we find that there are some serious gaps in the emissions data. The use of market-based instruments would necessitate a better reporting, monitoring and enforcement. Some researchers have shown (see Montero et al. 2000) that MBIs can be applied even if there are no continuous emissions monitoring systems installed. In fact, they argue that prospect of grand-fathering the emission quotas prompted the polluters to declare their emissions, thereby generating a better baseline set of emissions.

In the next chapter, I summarize the findings of my research, and conclude with policy implications, and further areas of research.

Chapter 9

Conclusion, Recommendations and Further Research

This thesis examined the following basic question: "what is the role of technology, specifically, the end-of-pipe emission control technologies, in achieving air pollution abatement targets in the Mexico City Metropolitan Area?" The need to reduce air pollution in the MCMA, and potential of further increases in the emissions due to the growth in the industrial and economic activity motivated my research. My analysis focused on modeling energy demand and emissions from the industrial sources in the MCMA, and incorporating technology and policy options, to identify the cost-effective strategies to achieve emissions abatement.

There are two principle reasons to focus on the industrial sources. First, although the contribution of industrial sources in the MCMA to the air pollution inventory is relatively small, specific point sources of air pollution may drive the secondary pollutant formation, such as ozone and fine particulate matter, in the MCMA. Second, various growth scenarios for the MCMA envisage an increasing role of industrial production in the regional economy, leading to an increased demand for energy, and increasing emissions. Moreover, significant reductions in the air pollution concentrations may necessitate that each source contribute to the abatement efforts for it may need a balanced portfolio of options to ensure political feasibility. The unit of analysis was the industries located in the MCMA. The system boundary for analysis was defined by the currently accepted definition of the Mexico City Metropolitan Area, which includes 16 delegations in the Federal District (*Distrito Federal* or DF) and 37 municipalities in the State of Mexico (*Estado de Mexico* or EM).

In this chapter, I present key results and findings of my research, discuss the role of institutions in implementing the policy recommendations, and outline the scope of further research.

9.1 Key Results and Findings

In this section, I present the key results and findings of my research. Specifically, I discuss the following:

- Structure of the MCMA industry and its implications
- The MCMA industrial energy-demand scenarios
- Emissions estimation and scenario analysis
- Multi-attribute tradeoff analysis
- Savings from the use of Market-based instruments
- Policy implications for the MCMA industrial sector

9.1.1 Structure of the MCMA Industry and its Implications

I analyzed recent changes in the structure of the MCMA industry, and identified a trend of increasing share of high energy-intensity chemical sub-sector, and declining share of the low energy-intensity metal-products sub-sector. To estimate the impact of this structural shift on the industrial energy demand in the MCMA, first I estimated energy intensity for the MCMA's industrial sub-sectors. I used industrial economic output and total industrial energy consumption data for the MCMA, and the industrial sub-sector energy intensity data from the US. Further, I used the macroeconomic growth data from the three Future Stories, and estimated energy demand by the MCMA industry for several scenarios.

Most scenarios indicate a significant increase in the future industrial energy demand (see Table 6.7) in the MCMA. Since emissions are directly related to the energy consumption, I concluded that the air pollution abatement goals cannot be met by aggressive decreases in energy intensity alone. The trend towards increasing output from the high-energy intensive chemical sub-sector needs to be halted or reversed, which has policy implications that are discussed later. This conclusion has led me to the following question. "If reducing industrial energy demand is not able to achieve emissions reduction, then what else can be done to reduce emissions?" Additional options, such as reducing the industrial output, or deploying end-of-pipe and process controls were then added to model the emissions scenarios.

9.1.2 Emissions Estimation and Scenario Analysis

I developed a model to estimate emissions by incorporating various technology and policy options (see Table 7.1). Specifically, I included exogenous growth rate of industry, energy intensity, and changes in the structure of industry (see Chapter 6) for modeling the MCMA industrial energy demand scenarios. Further, I included fuel-switching, policy influenced growth rate of the MCMA industry, end-of-pipe and process controls for NOx and PM reduction, as options to reduce emissions from the industrial sources (see Chapter 7).

Emissions estimations for the period 2000-2025 indicated that due to the strong influence of the factors affecting industrial growth in the MCMA, emissions are likely to increase significantly in most of the scenarios.

Most of the implementations of the technology and policy options could not achieve the ad hoc emissions abatement target of 50% reduction in annual industrial emissions of NO_x and PM_{10}, from the current (2001) levels in year 2025. Three key results (see Table 7.12) of the scenario analysis were as follows:

- The most aggressive implementation of technology options alone failed to meet the ad hoc target of 50% reduction in NO_x and PM_{10} emissions in 2025 from the base year (2001) levels.

- An aggressive deindustrialization policy, without combining with any other option, did achieve significant reductions, but only in the Changing Climates Future Story. However, deindustrialization alone was unable to meet the ad hoc abatement goal in the other two Future Stories.
- A combination of aggressive technology options coupled with fuel-switching, and SAEI reduction did perform better than deindustrialization alone, but did not attain the ad hoc reductions targets, except for PM_{10}, in the Growth Unbound Future Story.
- An integrated bundle of aggressive implementation of technology options and deindustrialization did show a significant decrease in the annual emissions across all the three Future Stories in 2025.

Although the integrated bundle of aggressive implementation of the technology and policy options did show significant decrease across all the Future Stories, it may be impractical to realize aggressive implementation of all the options simultaneously.

9.1.3 Multi-attribute Tradeoff Analysis

I estimated the emissions for each portfolio of options for each of the three Future Stories, for each year for the period 2000-2025. Further, I estimated cumulative emissions for the 25 year period for two pollutants of interest, PM_{10} and NO_x. The cost of implementation of the options was also estimated. I then estimated two metrics of costs, direct cost (also referred as capital cost), which included cost of installation, operation and maintenance of end-of-pipe and process controls, and policy cost, which also included the opportunity cost of foregone industrial output as a result of targeted deindustrialization policies.

I plotted tradeoff frontiers to analyze the implications of various strategies and their cost-effectiveness under different Future Stories. The two cost metrics resulted in different conclusions.

- Future Stories had a significant impact on cumulative emissions and cost performance of a strategy.
- Except in the Future Story - Divided City, the strategies were clustered around one of two dominant options, based upon the cost metric used. When we considered the capital cost alone, the clustering was around the policy option structure adjusted energy intensity (SAEI). When total policy cost was used, the clustering was around the option deindustrialization.
- The strategies on the tradeoff frontier corresponding to one pollutant did not necessary fall on the tradeoff frontier for another pollutant, but the deviation from the tradeoff frontier was relatively small. Therefore, generally the strategies which were good for one pollutant were also cost-effective for the other pollutant.
- Choice of the cost metric played a key role in determining the cost-effectiveness of strategies. A strategy on a tradeoff frontier when considering capital cost, did not find a place on the tradeoff frontier, when the total policy cost was considered.
- Fuel-switching was another important variable that appeared in most of the cost-effective strategies, but played a supporting role rather then being a dominant options since clean fuels are already in use in the MCMA.

9.1.4 Savings from the Use of Market-Based Instruments

To examine how the cost of implementation of some of the strategies discussed above, I looked at the heterogeneous abatement cost for the industrial sub-sectors and estimated savings from the use of the market-based instruments.

I used the sectoral abatement cost data for the US industries to estimate the potential savings of implementing various levels of emission reductions using the equimarginal principle, which is the key to achieve pollution abatement in the most efficient manner. I find that the savings from the use of market-based instruments are large enough. For example, for a 40% reduction in PM_{10} emissions, the use of MBIs could results in 75% savings as compared to the uniform reduction policy and warrant serious consideration for implementation in the MCMA.

9.2 Policy Implications and Recommendations

The scenario analysis and tradeoff plots indicate that the technology based solutions alone, particularly, installing end-of-pipe controls, are unable to achieve significant, sustained emissions reductions in the MCMA. The structure of the industry in the MCMA and changes in its energy intensity has significant role to play in determining industrial energy demand and therefore air pollutants emissions. Moreover, deindustrialization, coupled with the technology options, emerged as an important suite of the technology and policy options to achieve the ad hoc abatement target(50% reduction in the annual industrial emissions from the base year levels). Conventional command-and-control technology-forcing approach to achieve emissions reduction will likely not be sufficient in achieving substantial and sustained reductions. Therefore, managing the industry-mix in the MCMA should be a part of the industrial-environmental policy.

Deindustrialization, i.e., reducing the overall industrial activity in the MCMA, by identifying employment-neutral policy initiatives, such as move to increase the service sector, should be a part of the industrial-environmental policy in the MCMA.

9.2.1 The Institutional Framework for Policymaking and Implementation in the MCMA

I discussed the legal framework for the environmental policymaking in the MCMA, provided by the General Law for Ecological Balance and Environmental Protection, in Chapter 3 (see Section 3.6). According to the current environmental policymaking framework, the Mexican Ministry of Environment (SEMARNAT) is responsible for formulating environmental policy for industries in Mexico. At the local level, the local government bodies, such as Ministry of Environment for the DF and EM, are also engaged in industrial pollution regulation for the industries that fall within their jurisdictions (see Section 3.4). It is clear that to meet the environmental goals of air pollution reduction in the MCMA in a cost-effective manner, the abatement policies should address a very diverse set of options, listed in Table 9.1.

From the list of goals and mechanisms to achieve them, and the key institutions that could make it happen, it is clear that the environmental policymaking need to undergo a paradigm shift. Industrial policy, which often deals with the growth of industrial sector, needs to be combined with the environmental policy. The conventional approach of managing emissions is no longer sufficient. Therefore, the new paradigm for policymaking should be based on industrial-environmental policymaking. It should combine elements of conventional approaches of environmental management, with managing the industry-mix in a region, achieving energy efficiency, and promoting deindustrialization, if necessary.

Policies such as deindustrialization would mean compensating the foregone production either by shifting the manufacturing capacity to other regions, or by

Table 9.1 Technology and Policy Options, Implementation Mechanism, and Key Institutions

Technology/Policy Option	Implementation Mechanisms	Key Institutions
Reducing Energy Intensity	Provide incentives for capital stock turnover Energy auditing and energy efficiency improvement programs Changing the product-mix	Ministry of Economy SEMARNAT Ministry of Finance CONAE INE SMA (DF) SE (EM) SENER PEMEX
Increase Clean Fuel Fraction	Ensure adequate supply of natural gas Infrastructure for natural gas access to all industries	SENER PEMEX CRE
Adoption of End-of-Pipe and Process Emissions Control Technologies	Market-based mechanisms (Emissions trading, subsidy, fiscal incentives) Tariff Reduction for Importing Control Equipment	Ministry of Finance Ministry of Economy SEMARNAT SMA SE
Changing the Industry-mix	Incentives for cleaner industries (Electronics) Disincentives for dirtier Industries	Ministry of Economy, Ministry of Finance, SEMARNAT SMA (DF) SE (EM)
Deindustrialization	Incentives for migration of dirty Industries Job-training for industrial workers Promotion of commerce/services sectors	Ministry of Economy Ministry of Labour Ministry of Finance

Note: Please see list of abbreviations on page 17.

substituting the manufacturing capacity by increase in the services sector. Retraining for the newer jobs in the services sector could make the transition for the workers easier.

9.3 Future Research Directions

Several issues in this research could benefit from further work to improve the analysis.

9.3.1 Data and Data Sources

The emissions estimation for the MCMA industry are based on a limited set of establishments (as discussed in Chapter 6) that report their emissions to the authorities in the annual schedule of operations (*Cedula de Operation* or COA). The "missing" sources, such as small and medium size enterprises, could be a large source of emissions. Although it may be difficult or very expensive to track down every small establishment, modern statistical tools might be useful to sample smaller sources, and include their emissions in the emissions inventory and subsequent analysis.

The cost of abatement of NO_x and PM has been taken from the US data sources. There are no known NO_x controls installed in the MCMA (except that in the Jorge Luque power generation plant). However, there are several industries that report in the annual operations schedule COA about the use of particulate matter control equipment in their facilities. Better cost data for Mexican PM controls would improve the cost estimates.

The energy intensity and capital investment data were also based on capital stock turnover estimates which may or may not be energy intensity related. Energy-intensity specific capital investments in Mexican industries would be a better indicator of the actual cost of energy intensity reduction in the MCMA industry.

9.3.2 Additional Analysis

The technology and policy options analyzed as part of the scenario analysis have not only local but also global air pollution implications, which were not included in the analysis. Some of the options and strategies (for example deindustrialization) clearly reduce the local air pollution at the cost of increasing or at least shifting global air pollutant emissions. Policymakers could benefit from inclusion of such analysis.

The NO_x and PM controls (technology options) have not included any learning effects. The renewable-energy research has developed scholarly literature to study learning on the pace of cost reductions and the resultant investment in renewable energy technologies, particularly that of wind. The literature on control technologies does not offer any such indicators to take learning into account. Learning by the emissions control equipment manufacturers and their potential effect on abatement cost could be significant. This is clearly an area of scholarly research that could benefit from further work.

Political and institutional feasibility of techno-economic policy options depends on the cohesiveness of the political and environmental institutions in the MCMA. In this research I have briefly mentioned the jurisdictional issues, but have not included a detailed analysis of institutional framework for the industrial policy-making, which could have significant impacts on the implementation of particular options. Ultimately, the air quality management will be effective only if the local institutions can devise long-term plans and realize them by effective implementation, monitoring and enforcement.

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Appendix A: The Program Code

Note: The following Program was written in Microsoft© 's Visual Basic for Applications (VBA) to interface with the Microsoft Excel data sheets. Three spread-sheets were created in to store calculation results in a uniform format, for each of the Future Story, i.e., Growth Unbound, Changing Climates and Divided City. Emissions of various pollutants were estimated for different set of options, leading to a number of scenarios. Cost associated with each of the scenario was estimated and saved in the results sheet. Further, the net-present value of all the cost for the period 2000-2025, for different discount rates was calculated, and stored in a different sheet, to estimate analyze the different scenarios using the cumulative emissions and net present value of the cost. The code and the relevant spreadsheets to run the program can be had from the author, by sending an email at Samudra@mit.edu, or at <Samudra@alum.mit.edu>

```
Sub CreateScenarioName()
'Define parameter variables
'Param=Parameter AL for Activity Level
'EI: Energy Intensity
'CFR = Claen Fuel Ratio
'CPN = Control Population NOx
'CEN = Control Efficiency NOx Equipment
'CPPM = Control Population PM
'CEPM = Control Equipment Efficiency PM

' These are the values for the final scenario analysis
Dim CumNOx(729) As Single
Dim CumPM(729) As Single
'Dim NPV_EI_Capital(729) as Single
'NPV_EI_Capital is variable associated with investment in energy intensity efforts to reduce emissions
Dim NPV_Capital(729) As Single
```

```
Dim NPV_OandM(729) As Single
Dim NPV_AQProgram(729) As Single


Dim paramAL(3, 3) As Single
Dim paramEI(3, 3) As Single
Dim paramCFR(3, 3) As Single
Dim paramCPN(3, 3) As Single
Dim paramCEN(2, 3) As Single
Dim paramCPPM(3, 3) As Single
Dim paramCEPM(2, 3) As Single

'This variable Industrial Production stores the growth rates of Ind Out put for three future stories
Dim IndProd(26, 3) As Single

'Read parameter values from the spreadsheet
ActiveWorkbook.Sheets("Parameter Values").Select
ActiveSheet.Range("A1").Select

Dim i As Integer
Dim j As Integer

For i = 1 To 3
For j = 1 To 3
paramAL(i, j) = ActiveCell.Offset(3 + i, j).Value
paramEI(i, j) = ActiveCell.Offset(9 + i, j).Value
paramCFR(i, j) = ActiveCell.Offset(15 + i, j).Value
paramCPN(i, j) = ActiveCell.Offset(21 + i, j).Value
paramCPPM(i, j) = ActiveCell.Offset(32 + i, j).Value
Next j
Next i
```

```
For i = 1 To 2
For j = 1 To 3
paramCEN(i, j) = ActiveCell.Offset(27 + i, j).Value
paramCEPM(i, j) = ActiveCell.Offset(38 + i, j).Value
Next j
Next i

' Now read the Industrial Output Growth from the Sheet
ActiveWorkbook.Sheets("Manufacturing Production").Select
ActiveSheet.Range("A1").Select

For i = 1 To 26
For j = 1 To 3
IndProd(i, j) = ActiveCell.Offset(4 + i, 4 + j).Value
Next j
Next i

ActiveWorkbook.Sheets("Energy Consumption and Emission").Select
ActiveSheet.Range("A1").Select


Dim TotalNG(26) As Single
Dim TotalLPG(26) As Single
Dim TotalIF(26) As Single
Dim TotalElect(26) As Single
Dim TotalFossilEnergy(26) As Single
Dim TotalEnergy(26) As Single
Dim CFR(26) As Single

'Read Energy Consumpion for 1999
TotalNG(0) = ActiveCell.Offset(5, 1).Value
```

```
TotalLPG(0) = ActiveCell.Offset(5, 2).Value
TotalIF(0) = ActiveCell.Offset(5, 3).Value
TotalElect(0) = ActiveCell.Offset(5, 4).Value
TotalFossilEnergy(0) = ActiveCell.Offset(5, 6).Value
TotalEnergy(0) = ActiveCell.Offset(5, 7).Value
CFR(0) = ActiveCell.Offset(5, 5).Value

Dim NMHC(27) As Single
Dim NOX(27) As Single
Dim SO2(27) As Single
'Dim NH4(27) As Single
Dim PM(27) As Single
Dim CO(27) As Single
Dim CO2(27) As Single
Dim CH4(27) As Single

'Read emissions for 1999

NMHC(0) = ActiveCell.Offset(12, 1).Value
NOX(0) = ActiveCell.Offset(12, 2).Value
SO2(0) = ActiveCell.Offset(12, 3).Value
'NH3(0)= ActiveCell.Offset(12, 4).Value
PM(0) = ActiveCell.Offset(12, 5).Value
CO(0) = ActiveCell.Offset(12, 6).Value
CO2(0) = ActiveCell.Offset(12, 7).Value
CH4(0) = ActiveCell.Offset(12, 8).Value

'Read Emission Factors
Dim EF_ID_PM As Single
Dim EF_ID_SO2 As Single
Dim EF_ID_CO As Single
Dim EF_ID_NOx As Single
```

```
Dim EF_ID_HC As Single
Dim EF_ID_CO2 As Single

EF_ID_PM = ActiveCell.Offset(35, 1).Value
EF_ID_SO2 = ActiveCell.Offset(35, 2).Value
EF_ID_CO = ActiveCell.Offset(35, 3).Value
EF_ID_NOx = ActiveCell.Offset(35, 4).Value
EF_ID_HC = ActiveCell.Offset(35, 5).Value
EF_ID_CO2 = ActiveCell.Offset(35, 6).Value


Dim EF_LPG_PM As Single
Dim EF_LPG_SO2 As Single
Dim EF_LPG_CO As Single
Dim EF_LPG_NOx As Single
Dim EF_LPG_HC As Single
Dim EF_LPG_CO2 As Single

EF_LPG_PM = ActiveCell.Offset(18, 1).Value
EF_LPG_SO2 = ActiveCell.Offset(18, 2).Value
EF_LPG_CO = ActiveCell.Offset(18, 3).Value
EF_LPG_NOx = ActiveCell.Offset(18, 4).Value
EF_LPG_HC = ActiveCell.Offset(18, 5).Value
EF_LPG_CO2 = ActiveCell.Offset(18, 6).Value

Dim EF_NG_PM As Single
Dim EF_NG_SO2 As Single
Dim EF_NG_CO As Single
Dim EF_NG_NOx As Single
Dim EF_NG_HC As Single
Dim EF_NG_CO2 As Single
```

```
EF_NG_PM = ActiveCell.Offset(34, 1).Value
EF_NG_SO2 = ActiveCell.Offset(34, 2).Value
EF_NG_CO = ActiveCell.Offset(34, 3).Value
EF_NG_NOx = ActiveCell.Offset(34, 4).Value
EF_NG_HC = ActiveCell.Offset(34, 5).Value
EF_NG_CO2 = ActiveCell.Offset(34, 6).Value



' Read The Fuel Prices in million Mex Pesos

Dim Cost_NG(26, 3) As Single
Dim Cost_LPG(26, 3) As Single
Dim Cost_ID(26, 3) As Single
Dim Cost_Elect(26, 3) As Single

ActiveWorkbook.Sheets("Fuel Prices").Select
ActiveSheet.Range("A1").Select

'Read fuel prices ( Mexican Pesos/PJ)and convert it to MMxP/PJ
For i = 1 To 26
For j = 1 To 3
Cost_ID(i, j) = ActiveCell.Offset(1 + i, 8 * j - 3).Value / 1000000#
Cost_NG(i, j) = ActiveCell.Offset(1 + i, 8 * j - 2).Value / 1000000#
Cost_LPG(i, j) = ActiveCell.Offset(1 + i, 8 * j - 1).Value / 1000000#
Cost_Elect(i, j) = ActiveCell.Offset(1 + i, 8 * j).Value / 1000000#
Next j
Next i

'Read NOx control Penetration
ActiveWorkbook.Sheets("NOx Control").Select
ActiveSheet.Range("A1").Select
```

```
'Define and read maximum number of NOx controls
Dim MaxECNOx As Single
MaxECNOx = ActiveCell.Offset(0, 8).Value
'Read Cost of Capital Equipment for NOx Control in 2000USD
Dim Cost_EC_NOx_Cap As Single
Dim Cost_EC_NOx_OM As Single
Cost_EC_NOx_Cap = ActiveCell.Offset(0, 9).Value * 10
Cost_EC_NOx_OM = ActiveCell.Offset(0, 10).Value * 10

Dim PrcntECNOx(3, 3, 26) As Single
Dim k As Integer
For j = 1 To 3
For k = 1 To 26
PrcntECNOx(1, j, k) = ActiveCell.Offset(k + 6, j).Value
Next k
Next j

For j = 1 To 3
For k = 1 To 26
PrcntECNOx(2, j, k) = ActiveCell.Offset(k + 6, j + 3).Value
Next k
Next j

For j = 1 To 3
For k = 1 To 26
PrcntECNOx(3, j, k) = ActiveCell.Offset(k + 6, j + 6).Value
Next k
Next j

ActiveWorkbook.Sheets("PM Control").Select
ActiveSheet.Range("A1").Select
```

```
'Read Max No of PM Controls Possoble
Dim MaxECPM As Single
MaxECPM = ActiveCell.Offset(0, 8).Value
'Read Cost of a PM Control
Dim Cost_EC_PM_Cap As Single
Dim Cost_EC_PM_OM As Single
'Multiplied by 10 to convert USD in MxP
Cost_EC_PM_Cap = ActiveCell.Offset(0, 9).Value * 10
Cost_EC_PM_OM = ActiveCell.Offset(0, 10).Value * 10


Dim PrcntECPM(3, 3, 26) As Single


For j = 1 To 3
For k = 1 To 26
PrcntECPM(1, j, k) = ActiveCell.Offset(k + 4, j).Value
Next k
Next j


For j = 1 To 3
For k = 1 To 26
PrcntECPM(2, j, k) = ActiveCell.Offset(k + 4, j + 3).Value
Next k
Next j


For j = 1 To 3
For k = 1 To 26
PrcntECPM(3, j, k) = ActiveCell.Offset(k + 4, j + 6).Value
Next k
```

```
Next j

'Inflation Rate
ActiveWorkbook.Sheets("Inflation").Select
ActiveSheet.Range("A1").Select

Dim Inflation(26, 3) As Single
For i = 1 To 3
For j = 1 To 26
Inflation(j, i) = ActiveCell.Offset(j + 1, 1 + i).Value
Next j
Next i

Dim Avg_Inflation(3) As Single
For i = 1 To 3
Avg_Inflation(i) = ActiveCell.Offset(28, 1 + i)
Next i

'Defined Temporary Variables to Do the Calculations
Dim TempIndProd As Single
Dim TempAL As Single
Dim TempEI As Single
Dim TempCFR As Single
TempIndProd = 0
TempAL = 0
TempEI = 0
TempCFR = 0

'Dim strScenarioName(2916) As String
' An Array of Scenario Names is Declared which has 2916 elements, beginning with 0
Dim intCounti As Integer
Dim intCountj As Integer
```

```
Dim intCountk As Integer
Dim intCountl As Integer
Dim intCountm As Integer
Dim intCountn As Integer
Dim intCounto As Integer
Dim intCountp As Integer

Dim strScenarioName(2916) As String

Dim intNameCount As Integer
'The following string refers to Future Story, and can take value DC(Divided City) , CC(Climate Change), or GU(Growth Unbound)
Dim strFS As String
'Refers to Output/prodction by Industry
'Possible Values are
'CU = Current Level of Output
'MO = Moderate Reduction
'RE = Substantial Reduction
Dim strProd As String

'Refers to Change in Energy Intensity
'N = No change in EI
'M = Moderate Reduction
'S = Substantial Reduction
Dim strEI As String

'Refers to Fuel Swithcing
'Values,
'U = Current CFR
'O = Slow Switch
'A = Fast Change in CFR
Dim strCFR As String
```

```
'NOx Control Penetration
'Values; C - Current, M - Moderate Penetration, H - High Penetration
Dim strCPNOx As String
'Operation and Maintenance and Control Efficiency of NOx Control Equipment
'Values G = Good, B = Bad
Dim strCENOx As String
'PM Control Population and O & M
Dim strCPPM As String
Dim strCEPM As String

intCounti = 1
intCountj = 1
intCountk = 1
intCountl = 1
intCountm = 1
intCountn = 1
intCounto = 1
intCountp = 1

intNameCount = 1

For intCounti = 1 To 3
' This is for Fuel Switching(FS) Options
' C = Current Fuel Mix
' F= Fast Switching
' S = Slow Switching

  If intCounti = 1 Then
    strFS = "DC"
    Else
    If intCounti = 2 Then
      strFS = "CC"
```

```
  Else
    strFS = "GU"
  End If
End If
            If intCounti = 1 Then
              Workbooks.Open "ModelOutput_DC.xls", UpdateLinks:=0
            Else
              If intCounti = 2 Then
              ActiveWorkbook.Save
              ActiveWorkbook.Close
              Workbooks.Open "ModelOutput_CC.xls", UpdateLinks:=0
              Else
              ActiveWorkbook.Save
              ActiveWorkbook.Close
              Workbooks.Open "ModelOutput_GU.xls", UpdateLinks:=0
            'Workbook("ModelOutput.xls").Select
              End If
            End If



  For intCountj = 1 To 3
    'This is for Combustion and Process Efficiency (CPE)
    'E = Existing Efficiency
    'I = Improved Eff
    'A = Deteriorated Eff

    If intCountj = 1 Then
      strProd = "CU"
    Else
      If intCountj = 2 Then
        strProd = "MO"
```

```
    Else
        strProd = "RE"
    End If
End If

For intCountk = 1 To 3
    If intCountk = 1 Then
    strEI = "N"
Else
    If intCountk = 2 Then
        strEI = "M"
    Else
        strEI = "S"
    End If
End If


        For intCountl = 1 To 3
        ' Options for Control Population (CP)
        ' U - Current CP
        'I - for Modest Increase in CP
        'O - for High Increase in CP

        If intCountl = 1 Then
            strCFR = "U"
        Else

            If intCountl = 2 Then
                strCFR = "O"
            Else
                strCFR = "A"
            End If
```

```
End If

 For intCountm = 1 To 3


 If intCountm = 1 Then
    strCPNOx = "C"
 Else
    If intCountm = 2 Then
       strCPNOx = "M"
    Else
       strCPNOx = "H"
    End If
 End If

    'For intCountn = 2 To 2
    intCountn = 2

    'If intCountn = 1 Then
    '   strCENOx = "I"
    'Else
       strCENOx = "E"

    'End If

    For intCounto = 1 To 3


 If intCounto = 1 Then
    strCPPM = "C"
 Else
    If intCounto = 2 Then
```

```
        strCPPM = "M"
      Else
        strCPPM = "H"
      End If
    End If

      'For intCountp = 1 To 1
      intCountp = 1

      'If intCountp = 1 Then
        strCEPM = "I"
      'Else
      '  strCEPM = "E"

      'End If

      'End If

strScenarioName(intNameCount) = strFS & "-" & strProd & strEI & strCFR & strCPNOx & strCENOx & strCPPM & strCEPM
      'Application.StatusBar = "Running Scenario " & strScenarioName(intNameCount) & " Number " & intNameCount
      'If intNameCount = 1000 Then
      'MsgBox strScenarioName(intNameCount)
      'End If


    'If intNameCount = 2000 Then
     ' MsgBox strScenarioName(intNameCount)
    '  End If


      'Call the next subroutine to do the calculations/operations on data
```

```
        ' To Close Workbook Ind_2_7.xls
        'ActiveWorkbook.Save
        'ActiveWorkbook.Close

    ' Call Opensheet(strFS, strProd, strEI, strCFR, strCPNOx, strCENOx, strCPPM, strCEPM, intNameCount, paramAL, paramEI,
paramCFR, paramCPN, paramCEN, paramCPPM, paramCEPM, IndProd)

        'Open Workbook ModelOutput


         'Copy the result sheet, and write the scenario name in cell A1
         Dim strScenarioNameB As String
         strScenarioNameB = "INDUS-" & strFS & "-" & strProd & strEI & strCFR & strCPNOx & strCENOx & strCPPM
& strCEPM

         Sheets("Results").Select
         Sheets("Results").Copy Before:=Sheets(1)
         Sheets("Results (2)").Select
         Sheets("Results (2)").Name = strScenarioNameB
         ActiveSheet.Range("A1").Select
         ActiveCell.Value = strScenarioNameB

         ' Calculate Energy Consumption and Emissions
         TempAL = paramAL(intCountj, intCounti)
         TempEI = paramEI(intCountk, intCounti)
         TempCFR = paramCFR(intCountl, intCounti)
         Dim PrcntEnergy(26) As Single
         Dim FuelExpend(26) As Single
         Dim FinalPM(26) As Single
         Dim NO_EC_NOx(26) As Integer
         Dim NO_EC_PM(26) As Integer
```

```
Dim CapCost_NOx(26) As Single
Dim CapCost_PM(26) As Single
Dim OMCost_NOx(26) As Single
Dim OMCost_PM(26) As Single
NO_EC_NOx(0) = 0
NO_EC_PM(0) = 0
Dim Total_Cap_Cost(26) As Single
Dim Total_OM_Cost(26) As Single
Dim Total_Program_Cost(26) As Single


For k = 1 To 26
'Calculating Energy Consumption

TempIndProd = IndProd(k, intCounti)
PrcntEnergy(k) = (TempIndProd * (1 - TempAL / 100)) - TempEI
TotalEnergy(k) = TotalEnergy(k - 1) * (1 + PrcntEnergy(k) / 100)
TotalElect(k) = TotalElect(k - 1) * 1.03
TotalFossilEnergy(k) = TotalEnergy(k) - TotalElect(k)
'Assuming LPG consumption grows by 1% per annum
TotalLPG(k) = 1.01 * TotalLPG(k - 1)
CFR(k) = CFR(k - 1) + (TempCFR - CFR(0)) / 25
TotalNG(k) = TotalFossilEnergy(k) * CFR(k) - TotalLPG(k)
TotalIF(k) = TotalFossilEnergy(k) - TotalNG(k) - TotalLPG(k)


'Calculating Emissions
NMHC(k) = NMHC(k - 1) * (1 + PrcntEnergy(k) / 100)
NOX(k) = (EF_ID_NOx * TotalIF(k) + EF_NG_NOx * TotalNG(k) + EF_LPG_NOx * TotalLPG(k))
'Calculating impact of NOx Control Equipments on Emissions, assuming 50% efficiency
```

```
            NOX(k) = NOX(k) * (1 - PrcntECNOx(intCounti, intCountm, k) * 0.5 * (1 - paramCEN(intCountn, intCounti) / 100 / 26 * k) / 100)
            SO2(k) = SO2(k - 1) * (1 + PrcntEnergy(k) / 100)
            'NH3
            'PM Emission has two component, Energy related 60%, and Output related 40%
            PM(k) = ((0.4 * (PM(k - 1)) * (1 + PrcntEnergy(k) / 100)) + (0.6 * (EF_ID_PM * TotalIF(k) + EF_NG_PM * TotalNG(k) + EF_LPG_PM * TotalLPG(k))))
            'Calculaing the impcat of PM Control Equipment on Emissions, assuming 98% efficiency
            FinalPM(k) = PM(k) * (1 - PrcntECPM(intCounti, intCounto, k) * 0.98 * (1 - paramCEPM(intCountn, intCounti) / 100 / 26 * k) / 100)

            CO(k) = (EF_ID_CO * TotalIF(k) + EF_NG_CO * TotalNG(k) + EF_LPG_CO * TotalLPG(k))
            CO2(k) = ((EF_ID_CO2 * TotalIF(k) + EF_NG_CO2 * TotalNG(k) + EF_LPG_CO2 * TotalLPG(k)))
            CH4(k) = TotalNG(k)
        'Calculating Fuel Cost

            FuelExpend(k) = TotalIF(k) * Cost_ID(k, intCounti) + TotalNG(k) * Cost_NG(k, intCounti) + TotalLPG(k) * Cost_LPG(k, intCounti) + TotalElect(k) * Cost_Elect(k, intCounti)
        'Calculate Emission Control Cost
            NO_EC_NOx(k) = MaxECNOx * PrcntECNOx(intCounti, intCountm, k) / 100
            CapCost_NOx(k) = (NO_EC_NOx(k) - NO_EC_NOx(k - 1)) * Cost_EC_NOx_Cap
            OMCost_NOx(k) = NO_EC_NOx(k) * Cost_EC_NOx_OM

            NO_EC_PM(k) = MaxECPM * PrcntECPM(intCounti, intCounto, k) / 100
            CapCost_PM(k) = (NO_EC_PM(k) - NO_EC_PM(k - 1)) * Cost_EC_PM_Cap
            OMCost_PM(k) = NO_EC_PM(k) * Cost_EC_PM_OM

            Total_Cap_Cost(k) = CapCost_NOx(k) + CapCost_PM(k)
            Total_OM_Cost(k) = OMCost_PM(k) + OMCost_NOx(k)
            Total_Program_Cost(k) = 0.1 * Total_Cap_Cost(k)

            Next
```

```
    For k = 1 To 26
    ActiveCell.Offset(k + 1, 18).Value = Inflation(k, intCounti) * 100
    Next


    For k = 1 To 26
'Write the calculated Energy Values in the Cells
    ActiveCell.Offset(k + 1, 37).Value = TotalIF(k)
    ActiveCell.Offset(k + 1, 38).Value = TotalLPG(k)
    ActiveCell.Offset(k + 1, 39).Value = TotalNG(k)
    ActiveCell.Offset(k + 1, 44).Value = TotalElect(k)
    ActiveCell.Offset(k + 1, 45).Value = TotalEnergy(k)
    ActiveCell.Offset(k + 1, 15).Value = FuelExpend(k)
'Write Inflation in the fields
    ActiveCell.Offset(k + 1, 18).Value = Inflation(k, intCounti) * 100

'Write Emissions to The Result Sheet
    ActiveCell.Offset(k + 1, 1).Value = NMHC(k) / 1000#
    ActiveCell.Offset(k + 1, 2).Value = NOX(k) / 1000#
    ActiveCell.Offset(k + 1, 3).Value = SO2(k) / 1000#
    ActiveCell.Offset(k + 1, 5).Value = FinalPM(k) / 1000#
    ActiveCell.Offset(k + 1, 6).Value = CO(k) / 1000#
    ActiveCell.Offset(k + 1, 7).Value = CO2(k) / 1000#
    ActiveCell.Offset(k + 1, 8).Value = CH4(k) / 1000#
'Write Cost Data in Output Sheet
    ActiveCell.Offset(k + 1, 13).Value = Total_Cap_Cost(k) * ((1 + Avg_Inflation(intCounti)) ^ k) / 1000000#
'CRF is hardwired....assumed to be for loans of period 5 year, at rate of 14.1% per annum
    ActiveCell.Offset(k + 1, 14).Value = 1.46 * Total_Cap_Cost(k) * ((1 + Avg_Inflation(intCounti)) ^ k) / 1000000#

    ActiveCell.Offset(k + 1, 16).Value = Total_OM_Cost(k) * ((1 + Avg_Inflation(intCounti)) ^ k) / 1000000#
    ActiveCell.Offset(k + 1, 17).Value = Total_Program_Cost(k) * ((1 + Avg_Inflation(intCounti)) ^ k) / 1000000#
```

```
                Next
                ' Read and store values in an array to paste in scenario sheet

                CumNOx(intNameCount) = ActiveCell.Offset(29, 2).Value
                CumPM(intNameCount) = ActiveCell.Offset(29, 5).Value
                NPV_Capital(intNameCount) = ActiveCell.Offset(29, 14).Value
                NPV_OandM(intNameCount) = ActiveCell.Offset(29, 16).Value
                NPV_AQProgram(intNameCount) = ActiveCell.Offset(29, 17).Value

                intNameCount = intNameCount + 1

                 ' Next intCountp
                Next intCounto
              'Next intCountn
            Next intCountm
          Next intCountl
        Next intCountk
      Next intCountj
    Next intCounti
    ActiveWorkbook.Save
    ActiveWorkbook.Close

    ActiveWorkbook.Sheets("Scenarios").Select
    ActiveSheet.Range("A1").Select
```

```
    For j = 1 To 729
    ActiveCell.Offset(j, 1).Value = strScenarioName(j)
    ActiveCell.Offset(j, 2).Value = CumNOx(j)
    ActiveCell.Offset(j, 3).Value = CumPM(j)
    ActiveCell.Offset(j, 4).Value = NPV_Capital(j)
    ActiveCell.Offset(j, 5).Value = NPV_OandM(j)
    ActiveCell.Offset(j, 6).Value = NPV_AQProgram(j)
    Next

End Sub
```

Appendix B: A Sample Page of the Scenario Results

Scenario Name	Cumulative NOx (mt)	Cumulative PM_{10} (mt)	NPV Capital Cost (bMxP)	NPV Policy Cost (bMxP)
DC-CUNULELI	0.424	0.046	7.87	13.75
DC-CUNULEMI	0.424	0.043	11.20	28.43
DC-CUNULEHI	0.424	0.039	14.64	49.35
DC-CUNUMELI	0.420	0.046	10.31	16.21
DC-CUNUMEMI	0.420	0.043	13.64	30.89
DC-CUNUMEHI	0.420	0.039	17.08	51.81
DC-CUNUHELI	0.414	0.046	12.86	18.92
DC-CUNUHEMI	0.414	0.043	16.19	33.60
DC-CUNUHEHI	0.414	0.039	19.63	54.51
DC-CUNOLELI	0.412	0.044	7.87	13.75
DC-CUNOLEMI	0.412	0.041	11.20	28.43
DC-CUNOLEHI	0.412	0.038	14.64	49.35
DC-CUNOMELI	0.408	0.044	10.31	16.21
DC-CUNOMEMI	0.408	0.041	13.64	30.89
DC-CUNOMEHI	0.408	0.038	17.08	51.81
DC-CUNOHELI	0.402	0.044	12.86	18.92
DC-CUNOHEMI	0.402	0.041	16.19	33.60
DC-CUNOHEHI	0.402	0.038	19.63	54.51
DC-CUNALELI	0.393	0.041	7.87	13.75
DC-CUNALEMI	0.393	0.039	11.20	28.43
DC-CUNALEHI	0.393	0.036	14.64	49.35
DC-CUNAMELI	0.389	0.041	10.31	16.21
DC-CUNAMEMI	0.389	0.039	13.64	30.89
DC-CUNAMEHI	0.389	0.036	17.08	51.81
DC-CUNAHELI	0.384	0.041	12.86	18.92
DC-CUNAHEMI	0.384	0.039	16.19	33.60
DC-CUNAHEHI	0.384	0.036	19.63	54.51
DC-CUMULELI	0.409	0.044	11.70	16.64
DC-CUMULEMI	0.409	0.042	15.03	31.32
DC-CUMULEHI	0.409	0.038	18.47	52.23
DC-CUMUMELI	0.405	0.044	14.14	19.09
DC-CUMUMEMI	0.405	0.042	17.47	33.78

Note: For requesting a soft/hard copy of complete results table, please email Samudra@mit.edu or <Samudra@alum.mit.edu>